BENTON HARBOR POWER PLANT LIMNOLOGICAL STUDIES

PART XXXII

ENTRAINMENT OF PHYTOPLANKTON AT THE DONALD C. COOK NUCLEAR PLANT - 1980-1982

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XXXI. Phytoplankton of the seasonal surveys of 1980, 1981, and April 1982 and further pre- vs. postoperational comparisons at Cook Nuclear Plant. J. C. Ayers and L. E. Feldt. December 1983.

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INTRODUCTION

The Donald C. Cook Nuclear Plant is a 2,200 megawatt steam electric generating station situated on the southeastern shore of Lake Michigan about 18 km south of St. Joseph, Michigan. At full operation, the plant uses roughly 6,300 m^3/min of lake water in once-through cooling of its condensers; the water returned to the lake is 9-13C° above the intake temperature. Entrained phytoplankton are exposed to potentially damaging heat and pressure (in addition, prior to 1979, the plant used chlorination twice daily for chemical defouling of the heat exchangers and turbine condensers). Because algae form the base of the aquatic food chain, the effects of entrainment are of primary ecological importance. The Environmental Technical Specifications of the plant require an assessment of entrained phytoplankton abundance, viability, and species composition to be made on a monthly basis on samples collected in the early morning, at mid-day, and in the late evening.

SUMMARY OF OTHER STUDIES

Other power plant studies and pertinent phytoplankton research have been summarized in Rossmann et al. (1977). These studies have shown that phytoplankton may suffer inhibition or death as a result of condenser passage. Various authors have concluded that temperature rises which can be tolerated by phytoplankton range from 8C° to 11C°, although the actual change that can be tolerated is related to the initial water temperature (the lower the initial temperature, the greater the tolerable rise). If chlorination is also taking place, phytoplankton may be killed outright or suffer varying degrees of inhibition in productivity. In addition, changes in community structure have been

noted. At elevated temperatures, communities were observed to exhibit a decreased diversity promoted by a shift from a diatom-dominated community to one dominated by either green algae or blue-green algae. Some evidence also exists which suggests that phytoplankton productivity may be mildly stimulated by mechanical pumping.

PREVIOUS STUDIES AT THE COOK PLANT

Two major studies were initiated to investigate the impact of the power plant on the phytoplankton community. The first, begun in 1968, was concerned with the long-term effects of the plant on the phytoplankton community. The study included the determination of abundances and species composition in samples taken at both plant-influenced and non-influenced sites. These data established pre-operational phytoplankton trends and variations in the lake against which operational data can be compared. The results have been reported by Ayers et al. (1970), Ayers et al. (1971), Ayers et al. (1972), Ayers and Seibel (1973), Ayers et al. (1974), Ayers and Kopczynska (1974), Ayers (1975a), Ayers (1975b), Ayers et al. (1977), Ayers (1978), Ayers and Wiley (1979), Ayers and Feldt (1982), and Ayers and Feldt (1983).

The second study was begun in 1975 to ascertain the immediate effects of entrainment on the phytoplankton and to monitor long-term changes in the algal community. This study included the determination of phytoplankton abundance, species composition, and viability in samples taken from the intake and discharge forebays. The results for 1975, 1976, 1977, 1978, and 1979 are found in Rossmann et al. (1977), Rossmann et al. (1979), Rossmann et al. (1980), Chang et al. (1981a), and Rossmann et al. (1982), respectively. The results for 1980, 1981, and January through May 1982 are presented here.

SAMPLE HANDLING AND ANALYSIS

Sampling was conducted on a monthly basis with three approximately one-half hour sampling periods in a 24-hour span: after evening twilight, before morning twilight, and at noon. During each sampling period, fourteen to twenty-one samples were collected; seven from the intake forebay and seven from the discharge forebay of each operating unit (Fig. 1). Two of the seven samples from each location were preserved for microscopic investigation of phytoplankton abundance and species composition. The remaining five samples were used for spectrophotometric determination of chlorophylls *a*, *b*, and *c* and phaeophytin *a*. During the evening sampling period, five additional samples were collected from both the intake and discharge forebays. These samples were incubated at the intake temperature for approximately 36 hours and treated in the same manner as non-incubated samples for analysis of the chlorophylls and phaeophytin *a*. During the noon sampling period, six additional samples were collected from the intake forebay for nutrient analysis.

Water was collected from a depth of 5.5 meters by diaphragm pumps through 7.6-cm diameter hoses at a rate of roughly 227 L/min. As the water was pumped, the intake and discharge temperatures were taken and samples were collected in 1-L polyethylene bottles. Intake samples were taken from grate MTR 1-5, except in September 1981 when pump failure at MTR 1-5 necessitated sampling from MTR 1-4. Rossmann *et al*. (1977) and Chang *et al*. (1981a) established the uniformity of the sampling locations across the intake forebay; thus the September 1981 samples were included in the analysis without regard to sampling location. Unit 1 uses 2.7 x 10^6 liters of cooling water per minute. Therefore, the 5-L chlorophyll sample and the 2-L phytoplankton sample represent approximately

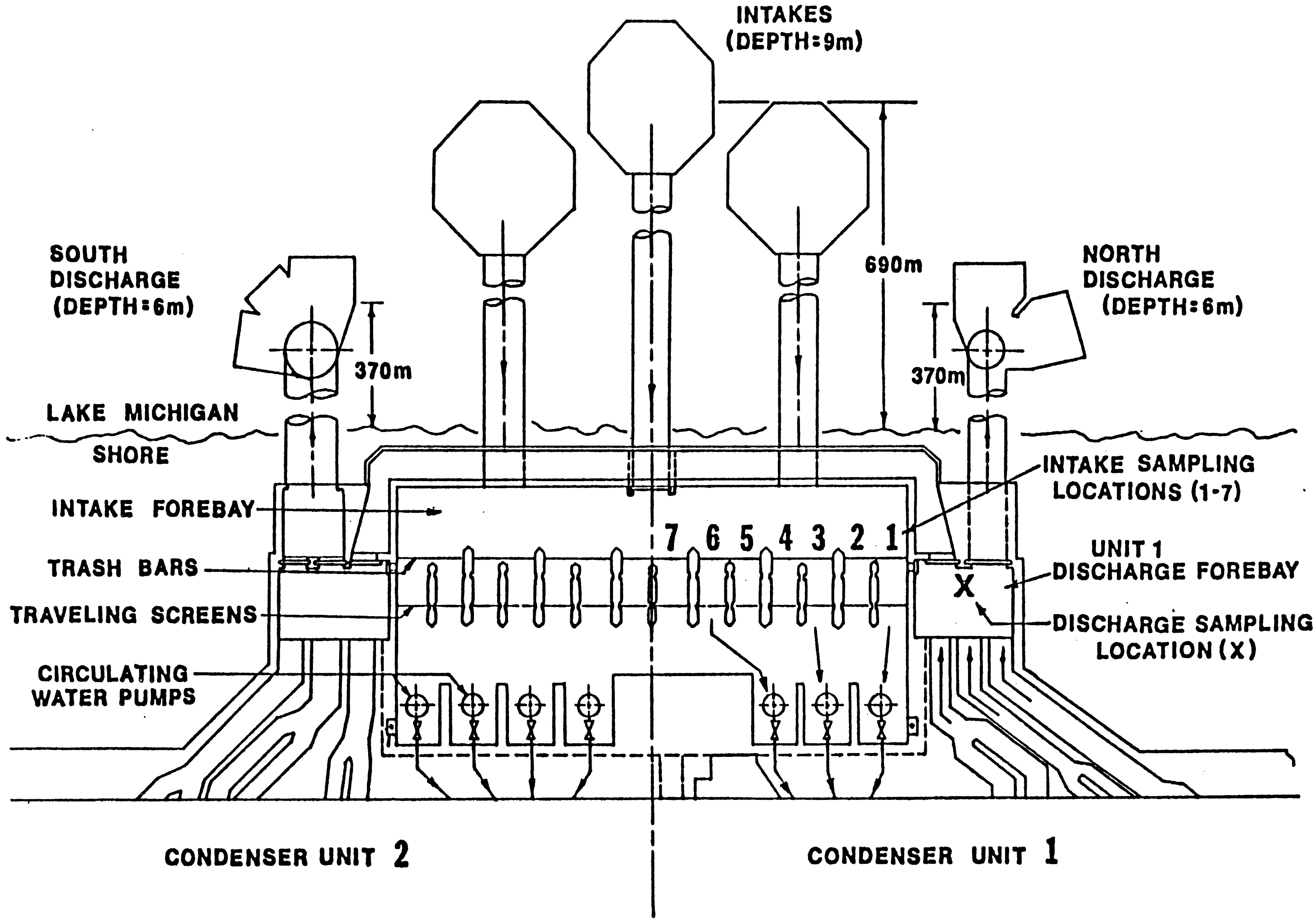

FIG. 1. Sampling locations in the Donald C. Cook Nuclear Plant screenhouse.

$6.2 \times 10^{-6}\%$ and $2.5 \times 10^{-6}\%$ of the water passing through the plant during a half-hour sampling period. Unit 2 uses 3.5×10^{6} liters per minute, so the chlorophyll and phytoplankton samples represent about $4.8 \times 10^{-6}\%$ and $1.9 \times 10^{-6}\%$ of the water passing through the plant during a sampling period. With both units operating, the percentages are $2.7 \times 10^{-6}\%$ for the chlorophyll sample and $1.1 \times 10^{-6}\%$ for the phytoplankton sample.

PHYTOPLANKTON

The replicate phytoplankton samples were collected in 1-L brown polyethylene bottles (triple rinsed with lake water) and fixed immediately with 6 mL of Lugols' iodine solution to kill the algae and stop bacterial degradation. Permanent slides were prepared in the Ann Arbor laboratory using the settle-freeze method of Sanford et al. (1969). The 1-L samples were transferred to graduated cylinders and left undisturbed for two days to allow the algae to sink to the bottom. After the settling period, 900 mL of supernatant was siphoned away, leaving a 100-mL concentrated stock sample. Each concentrated sample was then mixed and a portion pipetted into a settling chamber consisting of a plexiglass cylinder clamped to a standard microscope slide (Fig. 2). A thin layer of stopcock grease was used to form the seal between cylinder and slide. In most cases, the subsample to be settled was diluted so the algae on the resulting slide would be of countable density. Samples were left in the chambers for two days.

The settled algae were frozen onto the slide by carefully placing the entire chamber apparatus on a block of dry ice until the bottom 2-3 mm of sample had been frozen, about 25 seconds. The supernatant was then poured off, leaving the wafer of ice. After the ice melted, the cylinder was separated from the

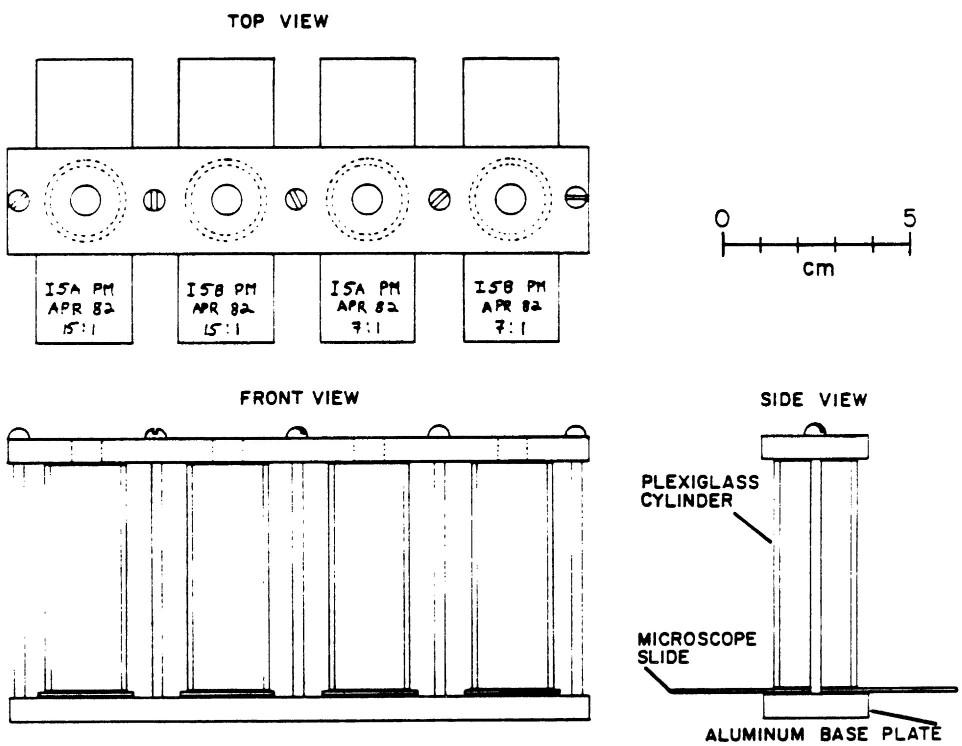

FIG. 2. Settling chamber for phytoplankton sample preparation.

slide. To prepare the sample for mounting, the slide was first placed in an anhydrous ethanol vapor for 2 days to dehydrate the sample and then in a toluene vapor for another 2 days to displace the ethanol. Finally, the algae were mounted under a cover-slip using Permount, a toluene-soluble mounting medium. The Permount required from 2 weeks to a month to harden before the slides could be counted.

The phytoplankton were examined at 1,000X to 1,250X using Leitz microscopes (Ortholux and Dialux) fitted with oil objectives, each having a numerical aperture of 1.32. Two complete 100-μm wide transects were made across each slide, one horizontal and one vertical, to help offset uneven distribution of cells on the slide. A minimum of 500 cells was counted for each slide to ensure reasonable group percentages. Additional transects were counted on slides with low density and those having a large proportion of cells in dense colonial formations (e.g., *Anacystis*, *Gomphosphaeria*, *Fragilaria*, *Tabellaria*). Individual cells were counted in all species except blue-green filaments with cylindrical trichomes (*Oscillatoria* and *Schizothrix*) for which whole filaments were counted. Identification was taken as far as possible for every cell encountered. The process was limited by the condition of the cell, the condition of the sample, and the state of the taxonomy for any given group. In many cases, the cells were identifiable only to genera or major group.

CHLOROPHYLLS AND PHAEOPHYTIN *a*

Immediately after collection, each 1-L water sample was passed through a 4.25-cm diameter Whatman GF/C glass fiber filter (beginning in April 1981, Reeve Angel 934 AH glass fiber filters were used). After most of the water had passed through the filter, 1 mL of saturated $MgCO_3$ was added (1 g $MgCO_3 \cdot 4H_2O$/100 g

distilled water). The measuring flask and filtration apparatus were rinsed with distilled water. Following filtration, the filters were rolled with forceps, placed in amber vials, frozen, and transported to Ann Arbor. The samples selected for incubation were not filtered at the time of collection but were immediately placed in an incubator with the bottle caps removed and allowed to incubate in the dark for 24 to 48 hours at the intake temperature. Following this, they were filtered and treated in the same manner as the non-incubated samples.

In the Ann Arbor laboratory, the frozen samples were prepared for analysis by grinding with a tissue grinder and extracting into 90% acetone using the method of Strickland and Parsons (1972). The 90% acetone was prepared by swirling reagent grade acetone with anhydrous Na_2CO_3 and passing it through a Whatman #4 filter (containing some additional Na_2CO_3) into a volumetric flask having the appropriate volume of distilled water for a 90% solution (v/v). Sample vials were removed from the freezer in groups of five and placed on ice in a dark ice chest next to the grinding apparatus. Sample vials were removed one at a time from the ice chest, and the frozen filters were transferred with forceps to a tissue grinding tube immersed in an icebath. The filter was ground at approximately 100 rpm for 4 minutes in 1.5 to 2 mL of 90% acetone in a tissue grinding tube; the grinding tube was held firmly against the rotating pestle, lowered briefly, and raised back against the pestle approximately every 15 seconds. If the filter and 90% acetone were not reduced to a homogeneous slurry after 4 minutes, grinding was continued until this was accomplished, generally within 1 more minute. The contents of the grinding tube were then poured into a 12-mL screw cap centrifuge tube. The tissue grinder was rinsed three times with 90% acetone into the centrifuge tube to adjust the final volume of 90% acetone to

10 mL. The centrifuge tube was then capped and returned to the ice chest. After all five samples were ground, they were placed in a dark refrigerator and allowed to extract for 24 to 36 hours. Following extraction, each sample was inverted three times, packed in ice, and centrifuged for 4 minutes at 2,000 rpm to separate the filter fibers and $MgCO_3$ from the extract. The centrifuged samples were then refrigerated until shortly before analysis.

For analysis, individual samples were warmed to room temperature in a light tight container. The extract was transferred using a Pasteur pipette to two 5-cm path cuvettes. Two drops of 50% v/v HCl were added to the sample in one cuvette, which was shaken and then held for 4 minutes. The other cuvette was placed in a Beckman model 25 scanning spectrophotometer where sample absorbances were measured between 600 and 750 nm. The absorbance of the acidified sample was then measured over the same range.

NUTRIENTS

After collection, the six 1-L nutrient samples were held at the intake temperature for about 30 minutes while the chlorophyll samples were being processed. Each nutrient sample was then passed through a membrane filter with a pore size of 45 μ and into a flask previously rinsed with the same filtrate. Approximately 450 mL of the filtered water was transferred to a 500-mL polyethylene bottle which had also been rinsed with a portion of the filtrate. Three of the samples were refrigerated and three were frozen.

In Ann Arbor, the samples were analyzed for orthophosphate, dissolved reactive silica, nitrate, and nitrite. The methods have been summarized

in Rossmann _et al_. (1979) and the quality control described in Rossmann _et al_. (1980).

CONDITIONS AT TIME OF COLLECTION

TEMPERATURE AND PHYSICAL EVENTS

Table 1 contains a summary of intake and discharge temperatures for those periods of time when phytoplankton entrainment samples were collected. In January 1980, the lake was notably turbid from a winter storm and the sample water was high in particulate matter. Unit 2 discharge temperatures were lower than usual because the unit had not returned to full power on the sampling dates. In April Unit 1 went down during a storm, resulting in the recorded temperature drop at the discharge forebay. Upwelling occurred the week before sampling in June and again during the September sampling period. In May 1981, stormy weather caused near-shore turbulence and resulted in samples high in particulates. Upwelling occurred during the week preceding the July entrainment sampling trip. Turbulent water was noted again in December. In January 1982, unseasonably high water temperatures were recorded, an indication of the plant's practice of deicing the intakes.

CHLORINATION

Previous to 1979, chlorination occurred twice daily at the Donald C. Cook Nuclear Plant. Chlorination ceased at the Cook Plant at the end of 1978.

Table 1. Intake and discharge entrainment temperatures for the sampling periods between January 1980 and May 1982. Dashes in the discharge columns indicate that unit was inoperative at the time of sampling.

Date	Time	Intake °C	Discharge #1, °C	Discharge #2, °C
21 Jan. 1980	Evening Twilight	-0.2	12.0	6.6
22	Morning Twilight	-0.3	12.0	6.5
22	Noon	-0.3	12.0	6.6
04 Feb. 1980	Evening Twilight	0.6	12.2	12.4
05	Morning Twilight	3.2	14.5	11.9
05	Noon	2.4	14.5	14.3
10 Mar. 1980	Evening Twilight	5.5	17.2	14.0
11	Morning Twilight	6.3	17.8	15.1
11	Noon	6.2	17.2	14.0
07 Apr. 1980	Evening Twilight	3.8	15.6	13.2
08	Morning Twilight	7.3	8.3	15.4
08	Noon	6.1	7.6	15.2
12 May 1980	Evening Twilight	11.9	23.0	21.4
13	Morning Twilight	12.5	23.8	22.2
13	Noon	12.5	24.0	22.4
09 Jun. 1980	Evening Twilight	14.7	--	24.1
10	Morning Twilight	14.0	--	25.5
10	Noon	13.0	--	23.1
14 Jul. 1980	Evening Twilight	22.5	--	31.1
15	Morning Twilight	22.3	--	31.8
15	Noon	23.6	--	32.8
11 Aug. 1980	Evening Twilight	23.8	31.1	33.5
12	Morning Twilight	24.2	31.9	34.0
12	Noon	23.0	31.1	33.0
08 Sep. 1980	Evening Twilight	20.1	29.3	29.5
09	Morning Twilight	22.9	31.5	31.0
09	Noon	22.5	33.2	32.2
13 Oct. 1980	Evening Twilight	16.0	26.2	24.6
14	Morning Twilight	14.0	25.1	22.9
14	Noon	15.2	25.4	23.7
10 Nov. 1980	Evening Twilight	10.5	20.6	--
11	Morning Twilight	9.2	19.5	--
11	Noon	9.3	19.5	--
08 Dec. 1980	Evening Twilight	6.4	16.9	--
09	Morning Twilight	7.7	17.9	--
09	Noon	6.8	16.0	--

(Continued)

Table 1. (Continued).

Date	Time	Intake °C	Discharge #1, °C	Discharge #2, °C
12 Jan. 1981	Evening Twilight	1.2	12.8	10.3
13	Morning Twilight	3.2	14.6	14.3
13	Noon	4.2	15.9	13.4
09 Feb. 1981	Evening Twilight	3.8	14.6	12.8
10	Morning Twilight	4.1	15.4	13.1
10	Noon	4.2	14.9	15.2
16 Mar. 1981	Evening Twilight	3.7	14.8	--
17	Morning Twilight	3.2	14.4	--
17	Noon	4.1	15.3	--
06 Apr. 1981	Evening Twilight	7.9	18.2	--
07	Morning Twilight	7.6	18.0	--
07	Noon	7.7	18.2	--
11 May 1981	Evening Twilight	9.2	19.6	--
12	Morning Twilight	10.1	19.7	--
12	Noon	8.9	19.5	--
08 Jun. 1981	Evening Twilight	17.7	--	26.8
09	Morning Twilight	17.4	--	25.3
09	Noon	17.9	--	26.8
13 Jul. 1981	Evening Twilight	23.7	--	29.3
14	Morning Twilight	23.5	--	29.9
14	Noon	23.2	--	33.8
08 Aug. 1981	Evening Twilight	25.0	31.9	33.9
09	Morning Twilight	25.7	31.9	35.2
09	Noon	25.3	31.8	33.2
14 Sep. 1981	Evening Twilight	22.0	33.4	31.6
15	Morning Twilight	22.5	34.0	32.8
15	Noon	23.2	34.7	32.1
12 Oct. 1981	Evening Twilight	14.5	25.4	--
13	Morning Twilight	14.3	25.0	--
13	Noon	14.4	25.2	--
09 Nov. 1981	Evening Twilight	10.1	--	19.2
10	Morning Twilight	10.1	--	21.0
10	Noon	10.9	--	19.7
07 Dec. 1981	Evening Twilight	9.1	21.0	18.5
08	Morning Twilight	6.0	15.7	17.7
08	Noon	5.2	14.9	16.8

(Continued)

Table 1. (Concluded).

Date	Time	Intake °C	Discharge #1, °C	Discharge #2, °C
12 Jan. 1982	Evening Twilight	9.8	21.0	19.3
13	Morning Twilight	10.3	19.8	20.0
18	Noon	10.1	20.6	19.7
08 Feb. 1982	Evening Twilight	1.2	--	10.2
09	Morning Twilight	1.8	--	11.0
09	Noon	1.4	--	10.8
08 Mar. 1982	Evening Twilight	1.0	11.0	12.0
09	Morning Twilight	1.0	11.8	10.4
09	Noon	0.2	11.3	10.2
12 Apr. 1982	Evening Twilight	7.9	19.7	17.2
13	Morning Twilight	3.6	16.0	14.9
13	Noon	3.8	15.4	13.9
10 May 1982	Evening Twilight	13.2	22.3	24.2
11	Morning Twilight	13.1	24.4	22.9
11	Noon	14.8	29.0	23.7

RESULTS AND DISCUSSION

NUTRIENTS

Availability of nutrients is one of the major environmental parameters (along with water temperature, light level, and grazing by zooplankton) influencing seasonal succession of the various groups of phytoplankton. Concentrations of orthophosphate, nitrate, nitrite, and dissolved reactive silica (Table 2) vary in response to utilization by the phytoplankton and bacteria, turnover (destratification), upwelling, and runoff. During periods when Lake Michigan is thermally stratified, the plant's intakes sample only epilimnetic water, where utilization is high and nutrient concentrations are usually low. Elevated nutrient levels at the intake result from several physical events. Runoff from the shore brings nutrients into the lake and upwelling forces nutrient-rich hypolimnetic water into the epilimnion. Most importantly, the entire water column is mixed at spring and fall turnover; and nutrients previously isolated by thermal stratification re-enter the surface regions.

In January 1980, orthophosphate and silica were considerably higher than the December 1979 values of 0.24 ppb and 0.25 ppm (Rossmann et al. 1982), and nitrite was detectable. The increase may have resulted from storm-induced turbulence. By March and April, the silica concentration was high again -- this time from the beginning of the spring turnover and possibly from runoff. Nitrite was also detectable in April. The diatom bloom was under way by May and the nutrient levels were decreasing, silica very dramatically. Upwelling occurred the week before sampling in June so nitrite was again present and silica rose slightly. In September, the silica concentration increased, probably due to another period of upwelling. Orthophosphate and nitrate increased in October

Table 2. Mean monthly variation of nutrients.

Month	Orthophosphate PO_4-P, ppb	Nitrate-N, ppm	Nitrite-N, ppm	SiO_2, ppm
1980				
January	0.762	0.23	0.0028	0.82
February	0.59	0.275	0.0	0.73
March	0.66	0.32	0.0	1.06
April	0.58	0.50	0.0127	1.36
May	0.35	0.40	0.0	0.27
June	0.11	0.34	0.0020	0.40
July	0.23	0.21	0.0	0.10
August	0.39	0.20	0.0	0.50
September	0.23	0.143	0.0	0.79
October	1.25	0.283	0.0	0.72
November	0.607	0.17	0.0	0.07
December	0.865	0.159	0.0	0.06
1981				
January	0.307	0.381	0.0	1.18
February	0.248	0.222	0.0	1.53
March	0.54	0.32	0.0	2.22
April	0.21	0.28	0.0030	0.80
May	0.12	0.43	0.0	0.93
June	0.32	0.11	0.0	0.85
July	0.362	0.264	0.0233	0.68
August	0.0751	0.222	0.0017	0.409
September	0.138	0.172	0.0	0.93
October	1.04	0.256	0.0040	1.42
November	0.0215	0.268	0.0128	1.02
December	1.83	0.481	0.0045	1.68
1982				
January	0.979	0.326	0.0	0.877
February	0.649	0.314	0.0	0.875
March	0.676	0.313	0.0	0.606
April	0.214	0.453	0.0017	1.200
May	0.041	0.030	0.0	0.314

with the onset of the fall turnover. By November and December, the winter pennate bloom had reduced the levels of orthophosphate, silica, and nitrate.

In January and February of 1981, silica levels were high, perhaps due to runoff. By March, the beginning of spring turnover, perhaps combined with the effects of runoff, resulted in a very high silica concentration and increasing orthophosphate. Utilization of nitrate, orthophosphate, and especially silica was evident in April, when the spring diatom bloom began. Nitrite was detected in April (during turnover) and again in July and August. Orthophosphate and silica levels generally continued to decrease until October when fall turnover mixed the water column and all nutrients increased. Utilization of orthophosphate and silica was evident again in November when diatom abundance peaked. Nitrite was also detectable in November. In December, all nutrient concentrations were high, presumably from storm-induced turbulence in the near-shore region.

From January through March 1982, nutrients generally decreased from the high levels observed in December 1981. In April, silica and nitrate increased and nitrite appeared with the onset of spring turnover. By May, the last sampling month, utilization of the nutrients by the phytoplankton was evident.

PHYTOPLANKTON

Monthly Variations of Entrained Major Phytoplankton Groups

The major groups of phytoplankton under consideration are coccoid blue-green algae, filamentous blue-green algae, coccoid green algae, filamentous green algae, flagellates, centric diatoms, pennate diatoms, desmids, and other algae. With the exception of the desmids, whose population level is relatively low throughout the year, all major groups represent significant contributions

to the composition of the total algal assemblage. The succession of diatoms, blue-green algae, green algae, and flagellates is of importance in this system (Rossmann et al. 1979). In general, these annual succession patterns are predictable year after year and are summarized in the paragraphs which follow.

Diatoms contribute the largest numbers to the total annual algal assemblage and include two major groups: centric and pennate diatoms. These groups, which have a close ecological affinity, are relatively abundant in spring (Rossmann et al. 1977, 1979, 1980; Chang et al. 1981a; Rossmann et al. 1982). They usually reach their peak in April and decrease thereafter. This decrease in abundance after April is most frequently related to the onset of thermal stratification, which isolates the surface waters from the pool of nutrients in the hypolimnion. At the same time, increases in diatoms accelerate the utilization of nutrients and result in nutrient depletion, especially depletion of dissolved silica, which is an essential element for diatom growth. The resulting low population density continues until October, when a decrease in water temperature and physical mixing processes create an isothermal water column. During the establishment of an isothermal water column, nutrients such as dissolved silica are replenished, leading to a relatively high density of diatoms throughout the winter months.

The green algae population, including coccoid green and filamentous green algae, is generally low from January through May or June. It reaches a peak density during the warm water months of May through September and then declines during October through December.

Blue-green algae are low in concentration from January through April for the filamentous and from January through July for the coccoid. Population abundance is highest during June through October when water temperatures are

relatively high, and its abundance decreases in November and December with decreased water temperature.

Flagellates are relatively low in concentration during January through March. A population peak generally occurs in April or May, and a large population often continues through December.

The patterns of succession described above serve as a general temporal distribution of species occurring in the offshore waters of Lake Michigan; but they are seldom completely coincident with the species found in the nearshore region of Lake Michigan, where environmental factors dominating the system vary greatly from year to year in degree and in time of occurrence. Furthermore, in the case of the entrainment samples, thermal effluents from the power generating plant offer an additional variable which may cause further deviations from the described patterns of succession. Because the general pattern of succession does not fully describe the existing yearly variations, it is of benefit to look at the observed patterns of 1980-82 algal succession. Entrained samples were collected for January 1980 through May 1982. Results will be discussed where feasible throughout the report. The complete results of microscopic counting of the 1980-82 phytoplankton entrained are in Appendix 1.

Comparisons between the total abundance of the coccoid blue-green algae in 1980-82 and those from 1975 to 1979 indicate a marked decrease with respect to 1975, 1976, and 1978; but an increase, with respect to 1977. 1980 showed an increase over 1979, with August-December having the greatest abundance. September 1981 had a peak abundance for the year (Table 3 and Fig. 3).

Filamentous blue-green algae were less numerous than coccoid blue-green algae and peaked in June 1980 and May 1981 (Table 4 and Fig. 4). Their abundance in 1980 was greater than that of 1977-79 and 1981 and less than those

Table 3. Monthly variation of coccoid blue-green algae from 1975 through May 1982 (cells/mL).

Month	1975'	1976'	1977'	1978'	1979'	1980'	1981'	1982'
January	461.(149.)			296.(91.9)	275.(44.5)	501.(143.)	279.(104.)	139.(21.6)
February	109.(59.7)	254.(71.7)		95.0(50.0)	120.(24.3)	130.(19.1)	98.3(21.8)	144.(29.3)
March	257.(186.)	347.(110.)	137.(57.2)	28.7(12.6)	209.(43.8)	102.(37.2)	40.5(14.1)	37.5(15.4)
April	312.(125.)	143.(63.6)	110.(76.2)	78.8(30.7)	30.0(27.6)	132.(34.6)	60.0(13.1)	57.1(27.2)
May	689.(169.)	87.1(46.6)	47.3(27.3)	142.(54.6)	171.(137.)	18.4(12.9)	188.(85.6)	66.0(27.2)
June	235.(155.)	33.6(25.1)	114.(45.6)	521.(166.)		311.(110.)	17.3(10.4)	
July	1,050.(155.)	57.8(26.5)	133.(28.5)	244.(75.7)	117.(27.6)	313.(63.7)	126.(86.4)	
August	286.(53.2)	439.(93.8)	1,210.(254.)	149.(35.4)	376.(53.1)	1,510.(240.)	426.(64.3)	
September	1,220.(169.)	339.(118.)	917.(93.6)	660.(80.4)	845.(138.)	1,100.(191.)	2,340.(363.)	
October	945.(212.)	560.(196.)	727.(145.)	2,350.(365.)	1,210.(142.)	1,830.(243.)	568.(153.)	
November	600.(166.)	422.(121.)	1,320.(289.)	1,990.(278.)	1,010.(119.)	1,670.(213.)	351.(84.4)	
December	176.(106.)	275.(73.4)	872.(124.)	3,640.(363.)	1,280.(174.)	1,320.(319.)	312.(76.0)	
Yearly Mean	535.(117.)	285.(50.1)	599.(159.)	850.(134.)	513.(144.)	745.(199.)	401.(183.)	88.7(22.1)

'Mean is followed by the standard error.

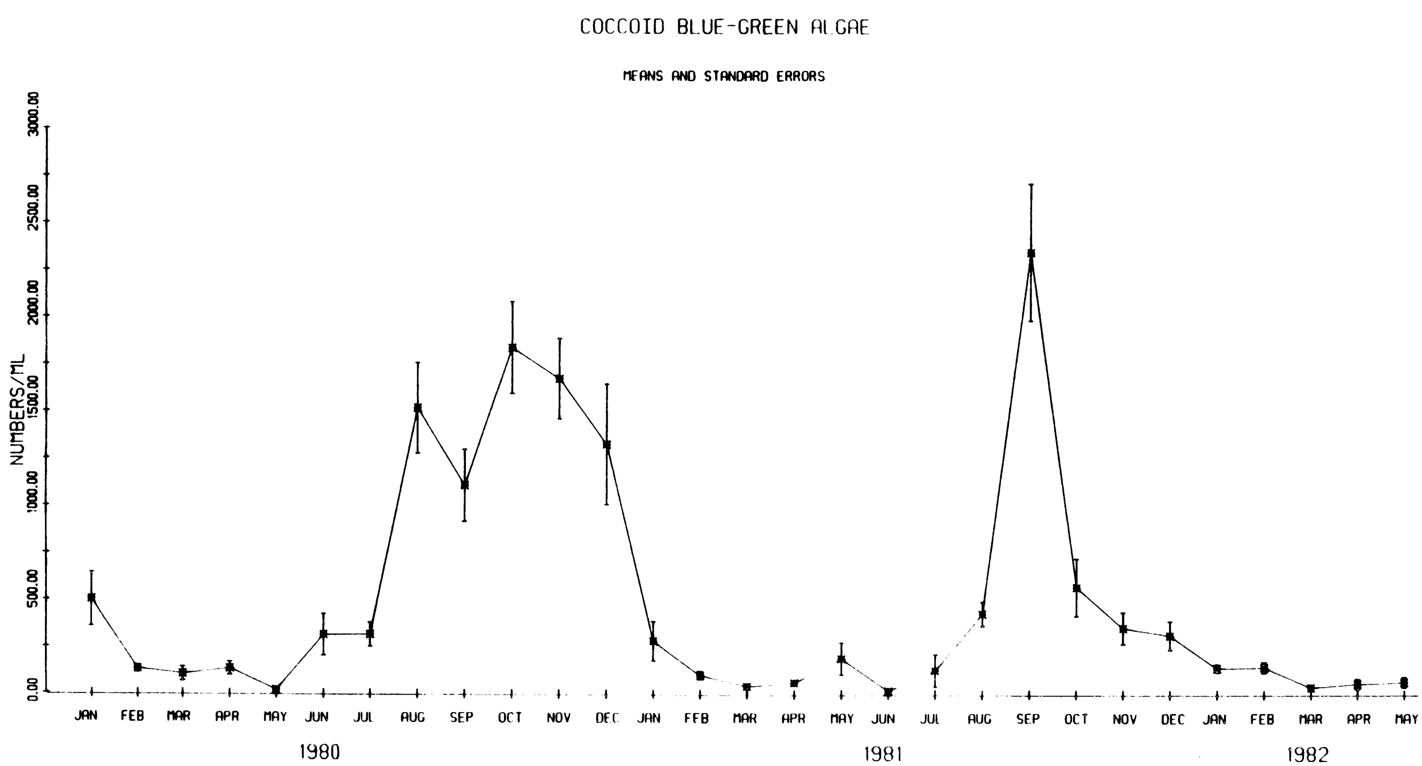

FIG. 3. Variation of coccoid blue-green algae numbers during 1980, 1981, and 1982.

Table 4. Monthly variation of filamentous blue-green algae from 1975 through May 1982 (cells/mL).

Month	1975[1]	1976[1]	1977[1]	1978[1]	1979[1]	1980[1]	1981[1]	1982[1]
January		22.0(8.06)		15.2(5.61)	7.91(1.33)	9.16(2.61)	21.5(4.15)	7.97(.868)
February	28.2(8.10)	16.4(3.53)		6.22(2.46)	3.78(0.60)	5.10(1.02)	9.89(1.12)	13.5(3.18)
March	59.7(17.6)	13.4(2.53)	16.7(3.19)	3.60(.921)	4.57(0.86)	7.73(1.55)	8.49(2.45)	18.0(3.31)
April	27.6(5.40)	57.9(5.16)	110.(76.2)	2.63(.919)	3.58(1.71)	3.37(0.86)	33.8(6.22)	3.13(1.06)
May	103.(37.0)	457.(52.8)	17.5(4.09)	14.4(4.53)	15.5(5.63)	54.5(15.3)	111.(23.0)	11.6(1.63)
June	314.(38.1)	81.1(16.1)	24.3(8.29)	111.(51.9)		312.(110.)	50.4(7.85)	
July	95.1(25.5)	72.1(12.7)	59.9(14.3)	65.0(12.6)	201.(29.3)	211.(65.1)	73.5(26.7)	
August	8.90(2.70)	9.24(3.08)	17.6(6.37)	111.(26.5)	20.1(5.09)	62.1(18.7)	29.0(6.62)	
September	17.3(9.20)	46.8(15.8)	25.0(8.84)	8.89(2.68)	41.8(5.81)	26.4(5.94)	33.7(11.2)	
October	98.8(34.0)	45.9(23.8)	21.4(7.61)	87.0(18.9)	115.(18.2)	50.7(19.0)	9.39(3.22)	
November	21.6(17.8)	6.35(4.31)	12.7(3.13)	82.9(18.7)	38.3(9.60)	69.9(23.3)	7.73(1.97)	
December	15.4(7.70)	74.5(44.3)	45.2(18.6)	67.9(13.5)	5.38(1.91)	14.9(8.17)	17.9(3.32)	
Yearly Mean	71.8(26.5)	75.2(35.6)	35.0(9.54)	48.0(13.3)	41.5(18.7)	68.9(27.6)	33.8(8.98)	10.8(2.52)

[1]Mean is followed by the standard error.

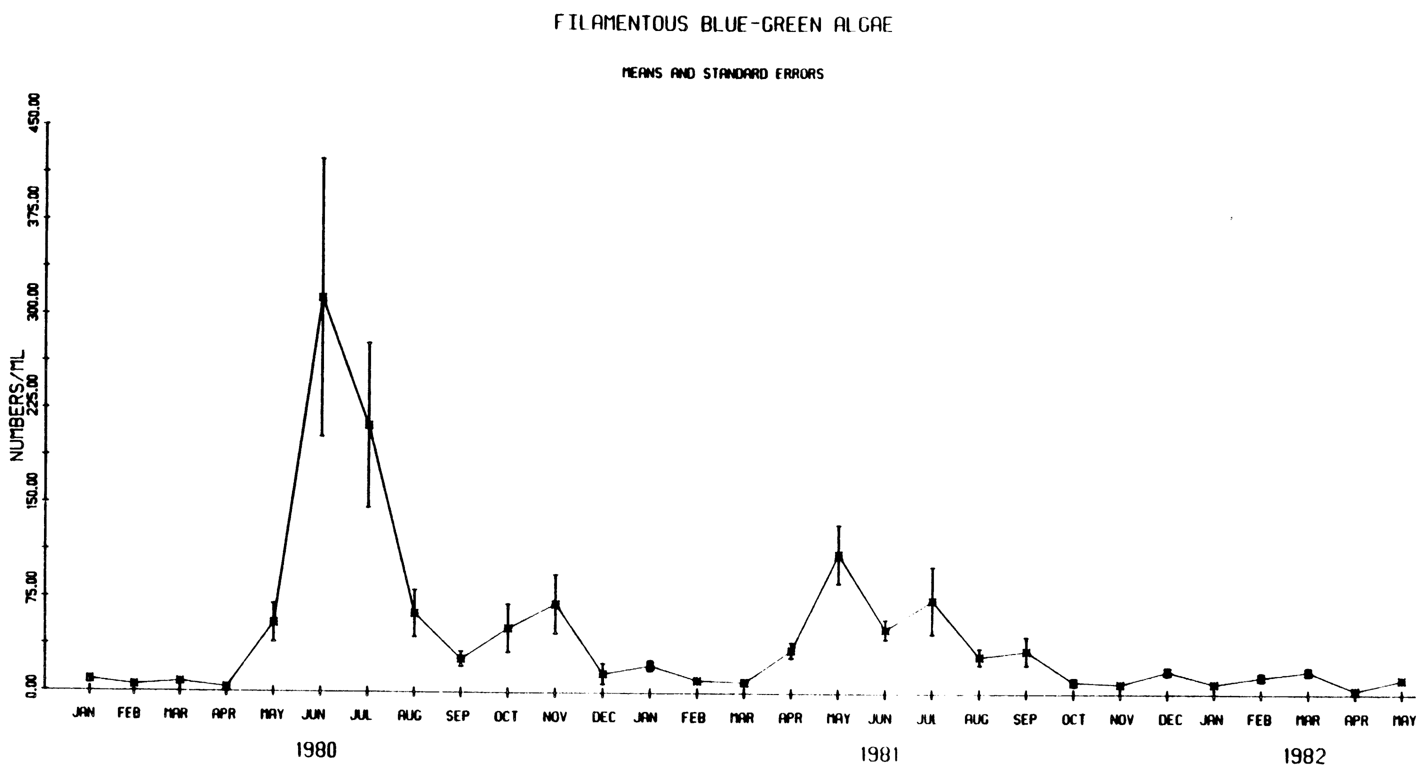

FIG. 4. Variation of filamentous blue-green algae numbers during 1980, 1981, and 1982.

of 1975 and 1976. Monthly abundances in 1982 were less than those in 1980 and 1981, except for February and March.

The mean population for coccoid green algae was quite variable between 1975 and 1982 (Table 5 and Fig. 5). There was an increase in mean population density between 1975 and 1976, a decrease between 1976 and 1977, an increase between 1977 and 1978, a decrease between 1978 and 1979, and an increase in 1980 and 1981. Peak abundances in 1980 were in July, August, and September; and in 1981, they were in July.

Filamentous green algae were less numerous than coccoid green algae and had a population density above 10 cells/mL in December 1979, and May, June, and December 1981 (Table 6 and Fig. 6). The 1980 yearly average of this group is the lowest for the years 1975 througn 1981.

Flagellates were numerous and contributed a large portion to the total annual algal population in 1980-81 (Table 7 and Fig. 7). In 1980, flagellates peaked in April with high abundances through September. A high density in June 1981 was followed by higher abundances than in previous years for the remainder of the year. Total abundances for 1981 and 1982 were higher than in previous years, an indication that flagellates may be increasing overall.

Centric diatoms peaked in May 1980 and 1981 and in April 1982 (Table 8 and Fig. 8). They peaked again, but not as much, in September 1980 and 1981. Highest population density from 1975-1982 was in May 1981, thus giving that year the highest yearly mean.

Pennate diatoms contributed a large share to the total algal population in each year samples were collected (Table 9 and Fig. 9). They were always low in density in spring, reached a peak in April or May, and decreased in July

Table 5. Monthly variation of coccoid green algae from 1975 through May 1982 (cells/mL).

Month	1975'	1976'	1977'	1978'	1979'	1980'	1981'	1982'
January	42.2(12.2)			56.8(17.4)	39.6(4.87)	70.5(32.9)	74.9(11.9)	23.2(7.94)
February	39.3(14.2)	29.5(11.1)		10.7(2.57)	18.5(3.53)	24.3(5.37)	38.2(6.95)	37.2(10.6)
March	55.2(24.7)	22.9(7.63)	21.1(4.43)	16.6(4.54)	79.4(43.5)	50.6(10.4)	46.2(8.06)	47.5(11.9)
April	49.7(14.8)	57.9(12.3)	51.4(8.31)	108.(25.2)	69.9(22.5)	48.3(6.90)	72.4(12.2)	43.5(10.9)
May	47.1(19.7)	145.(30.6)	15.3(4.89)	145.(23.6)	125.(18.1)	86.2(33.6)	95.1(23.6)	62.5(14.8)
June	141.(23.2)	98.4(26.9)	39.2(15.8)	150.(45.3)		111.(31.9)	29.8(8.45)	
July	1,000.(107.)	689.(123.)	152.(19.2)	103.(36.0)	54.9(15.2)	443.(35.2)	356.(32.6)	
August	197.(37.1)	494.(46.8)	115.(16.5)	166.(33.0)	153.(21.6)	407.(63.9)	178.(36.8)	
September	176.(24.2)	755.(129.)	54.4(8.31)	174.(24.1)	95.6(10.6)	433.(66.8)	176.(51.0)	
October	116.(16.1)	242.(37.1)	232.(85.4)	256.(26.9)	132.(12.9)	146.(23.9)	86.1(14.2)	
November	138.(66.9)	134.(36.1)	65.1(18.2)	159.(18.1)	77.9(15.0)	159.(41.6)	67.7(16.0)	
December	110.(47.8)	240.(54.4)	49.5(11.4)	194.(15.1)	133.(29.9)	62.6(14.5)	33.2(12.2)	
Yearly Mean	188.(82.8)	246.(74.6)	79.5(21.5)	128.(22.6)	89.0(12.9)	170.(46.2)	104.(27.0)	42.7(6.43)

'Mean is followed by the standard error.

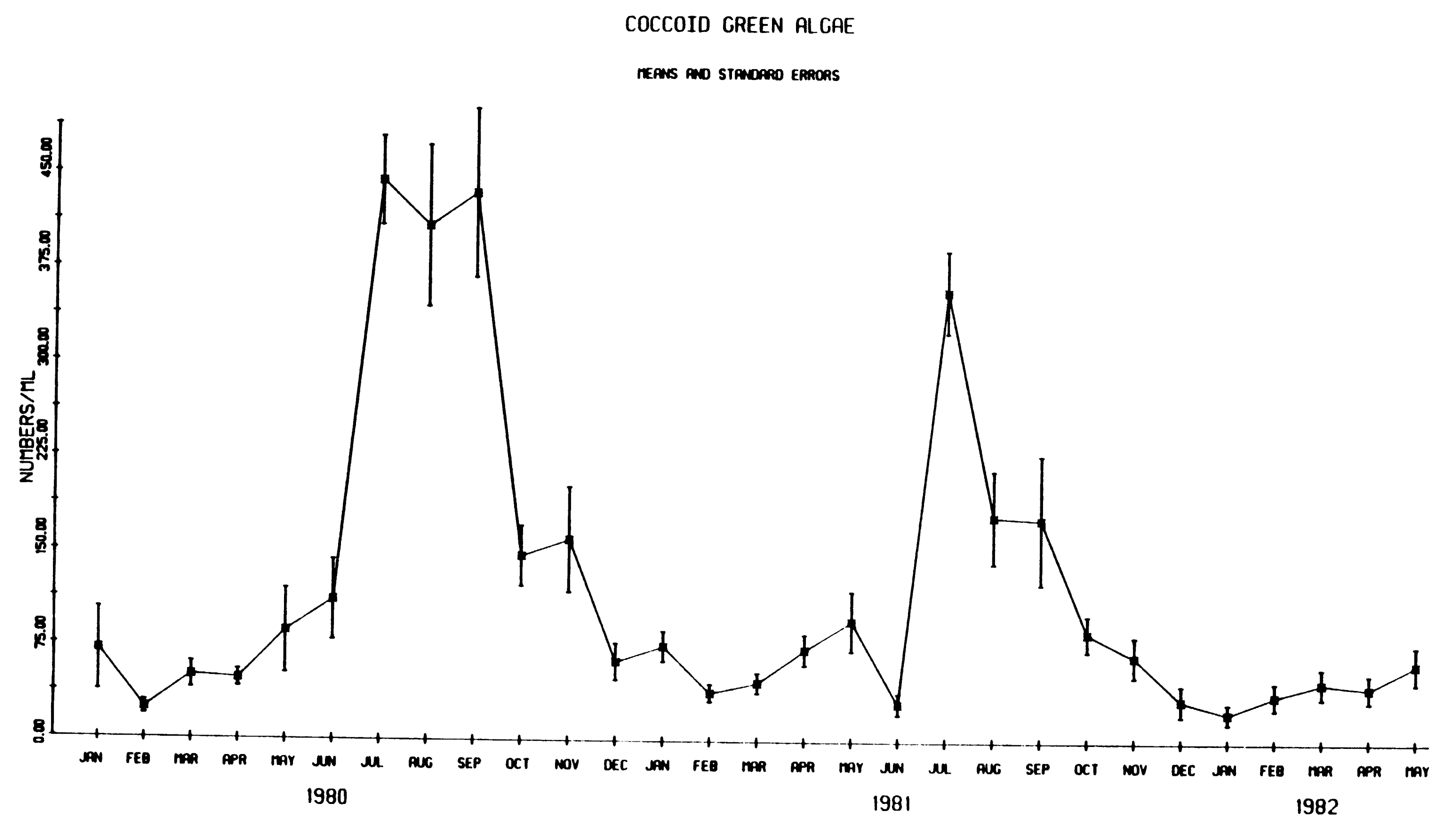

FIG. 5. Variation of coccoid green algae numbers during 1980, 1981, and 1982.

Table 6. Monthly variation of filamentous green algae from 1975 through May 1982 (cells/mL).

Month	1975'	1976'	1977'	1978'	1979'	1980'	1981'	1982'
January	31.6(17.4)			2.26(1.35)	2.49(0.89)	1.46(0.85)	4.79(1.24)	2.49(.797)
February	18.0(9.70)	2.00(1.20)		.350(.241)	0.278(0.280)	0.0(0.0)	.828(.307)	1.18(1.03)
March	34.8(12.6)	16.4(6.62)	6.63(4.37)	3.04(1.82)	0.600(0.330)	0.550(0.40)	.142(.142)	3.87(1.66)
April	0.0(0.0)	18.1(10.5)	18.2(12.3)	2.21(1.70)	0.00(0.00)	0.094(0.09)	2.22(.939)	0.0(0.0)
May	1.50(1.50)	57.8(23.0)	4.63(2.32)	1.70(1.15)	0.00(0.0)	8.66(3.55)	85.1(70.3)	1.57(.646)
June	29.5(20.6)	55.0(14.0)	.417(.417)	2.62(1.03)		1.37(0.75)	11.7(5.85)	
July	0.3(0.3)	37.3(11.1)	22.9(4.79)	11.2(2.82)	4.34(1.40)	0.0(0.0)	2.22(1.39)	
August	0.8(0.6)	4.28(2.52)	0.0(0.0)	8.15(2.83)	.228(0.228)	2.94(1.04)	.644(.447)	
September	0.2(0.2)	13.7(6.13)	1.86(.888)	1.12(.401)	.700(0.523)	5.57(2.55)	1.48(1.01)	
October	2.8(1.1)	9.67(2.47)	6.63(4.02)	8.19(2.16)	5.53(1.61)	1.93(0.85)	3.32(3.32)	
November	1.5(1.2)	6.35(5.48)	26.8(6.92)	18.4(4.37)	0.0(0.0)	0.275(0.27)	7.47(3.42)	
December	14.4(7.3)	5.52(2.39)	14.0(6.97)	35.4(4.55)	12.3(7.81)	3.04(1.30)	16.2(4.27)	
Yearly Mean	9.44(3.87)	21.5(5.64)	10.2(3.06)	7.92(2.03)	2.41(1.14)	2.16(0.76)	11.3(6.85)	1.82(.649)

'Mean is followed by the standard error.

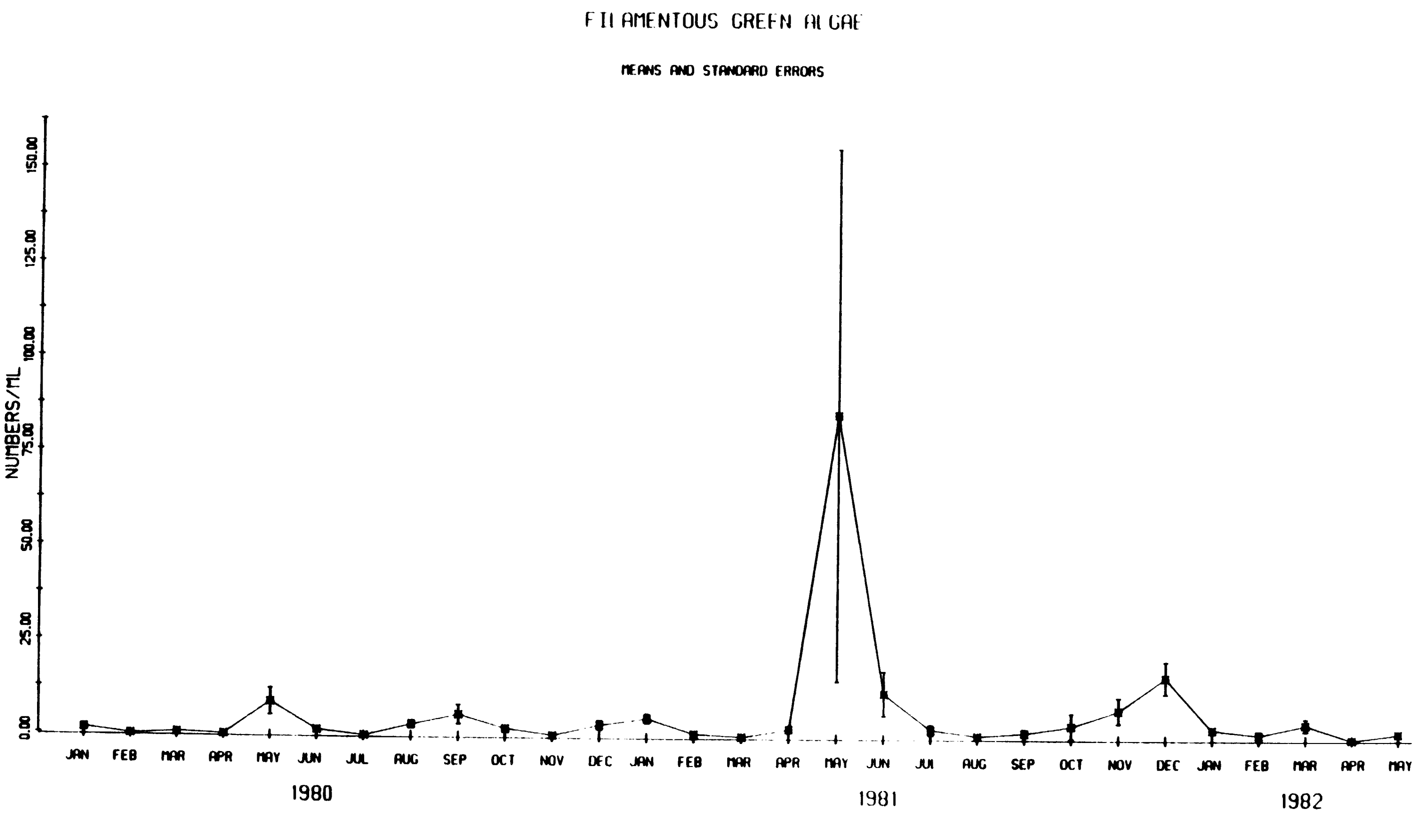

FIG. 6. Variation of filamentous green algae numbers during 1980, 1981, and 1982.

Table 7. Monthly variation of flagellated algae from 1975 through May 1982 (cells/mL).

Month	1975'	1976'	1977'	1978'	1979'	1980'	1981'	1982'
January	110.(18.7)			156.(44.0)	277.(53.2)	446.(69.4)	252.(25.9)	216.(24.0)
February	90.8(20.8)	252.(32.1)		109.(21.7)	242.(46.7)	264.(21.0)	462.(37.9)	666.(68.1)
March	272.(56.6)	268.(25.5)	628.(60.2)	97.5(24.6)	392.(37.1)	291.(25.5)	1,010.(102.)	925.(77.8)
April	857.(190.)	351.(36.6)	1,010.(116.)	435.(69.9)	379.(44.4)	775.(59.5)	756.(86.8)	987.(97.8)
May	641.(82.3)	1,350.(220.)	1,200.(160.)	728.(153.)	625.(80.5)	499.(66.8)	1,560.(196.)	644.(61.2)
June	802.(148.)	633.(70.5)	235.(30.6)	2,840.(275.)		513.(79.5)	2340.(213.)	
July	561.(94.6)	452.(31.6)	267.(33.9)	395.(77.7)	534.(51.4)	635.(63.2)	853.(106.)	
August	504.(56.7)	482.(86.6)	376.(31.9)	191.(18.9)	227.(34.9)	494.(52.7)	867.(72.5)	
September	587.(71.6)	426.(70.3)	302.(57.8)	75.7(11.5)	274.(38.7)	422.(99.5)	1,210.(157.)	
October	696.(85.4)	559.(91.7)	550.(91.8)	108.(15.9)	249.(34.9)	113.(26.7)	1,250.(174.)	
November	417.(51.9)	524.(47.6)	754.(156.)	52.0(12.4)	444.(29.4)	127.(36.7)	912.(93.0)	
December	368.(59.9)	415.(84.2)	78.9(19.3)	261.(88.0)	486.(66.0)	66.0(13.2)	660.(63.5)	
Yearly Mean	527.(69.0)	485.(89.0)	540.(114.)	454.(68.9)	375.(40.5)	387.(63.2)	1,010.(158.)	688.(136.)

'Mean is followed by the standard error.

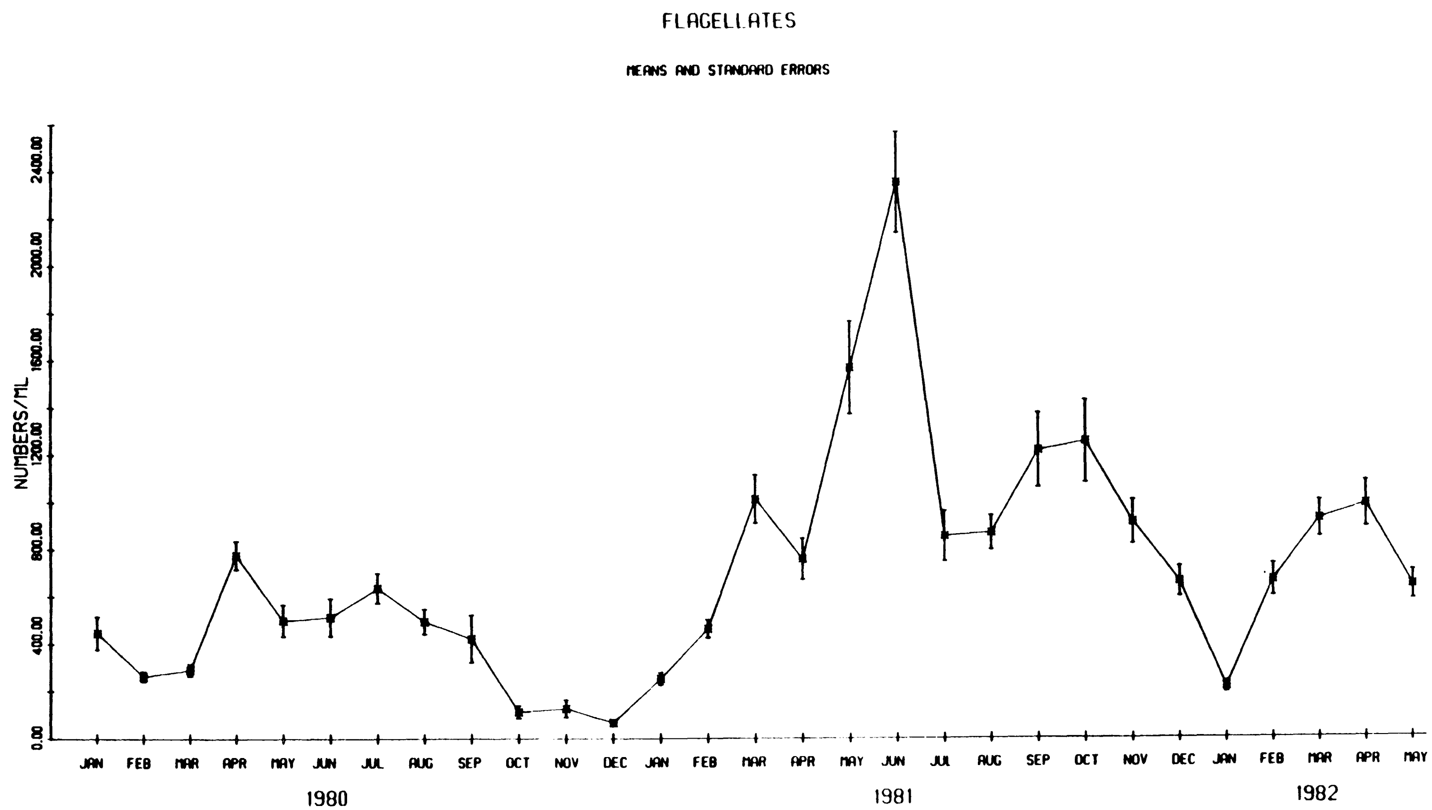

FIG. 7. Variation of flagellated algae numbers during 1980, 1981, and 1982.

Table 8. Monthly variation of centric diatoms from 1975 through May 1982 (cells/mL).

Month	1975[1]	1976[1]	1977[1]	1978[1]	1979[1]	1980[1]	1981[1]	1982[1]
January	1,810.(191.)			310.(46.7)	193.(11.8)	253.(23.7)	434.(18.2)	173.(9.62)
February	1,040.(130.)	560.(45.0)		125.(12.8)	169.(8.96)	205.(11.9)	213.(16.5)	185.(14.5)
March	1,290.(111.)	807.(56.8)	463.(57.7)	423.(37.8)	352.(22.2)	337.(28.8)	830.(52.6)	541.(51.2)
April	2,550.(427.)	930.(51.1)	779.(83.9)	592.(74.5)	2,590.(199.)	310.(17.7)	798.(38.8)	2,150.(142.)
May	1,190.(170.)	1,400.(189.)	139.(23.1)	1,800.(168.)	428.(28.4)	2,330.(176.)	4,200.(326.)	170.(17.4)
June	817.(64.3)	212.(18.3)	451.(91.5)	1,450.(141.)		1,800.(163.)	35.1(4.58)	
July	914.(108.)	3,370.(361.)	967.(65.9)	1,100.(99.6)	78.8(6.89)	148.(12.1)	119.(9.48)	
August	132.(23.9)	272.(25.9)	175.(12.0)	200.0(30.0)	96.3(9.88)	547.(92.9)	1,480.(68.5)	
September	69.2(8.3)	1,060.(157.)	183.(14.8)	225.(40.5)	247.(28.2)	1,880.(101.)	2,450.(164.)	
October	286.(21.2)	644.(50.9)	140.(18.1)	904.(88.7)	511.(53.0)	806.(40.1)	682.(47.4)	
November	404.(64.5)	1,090.(69.4)	194.(24.2)	195.(21.3)	240.(14.3)	527.(74.1)	2,040.(94.1)	
December	1,700.(132.)	503.(58.8)	165.(18.5)	160.(9.63)	368.(34.1)	578.(58.5)	1,110.(55.5)	
Yearly Mean	945.(224.)	1,050.(249.)	366.(93.7)	623.(64.0)	479.(214.)	810.(217.)	1,200.(348.)	645.(384.)

[1]Mean is followed by the standard error.

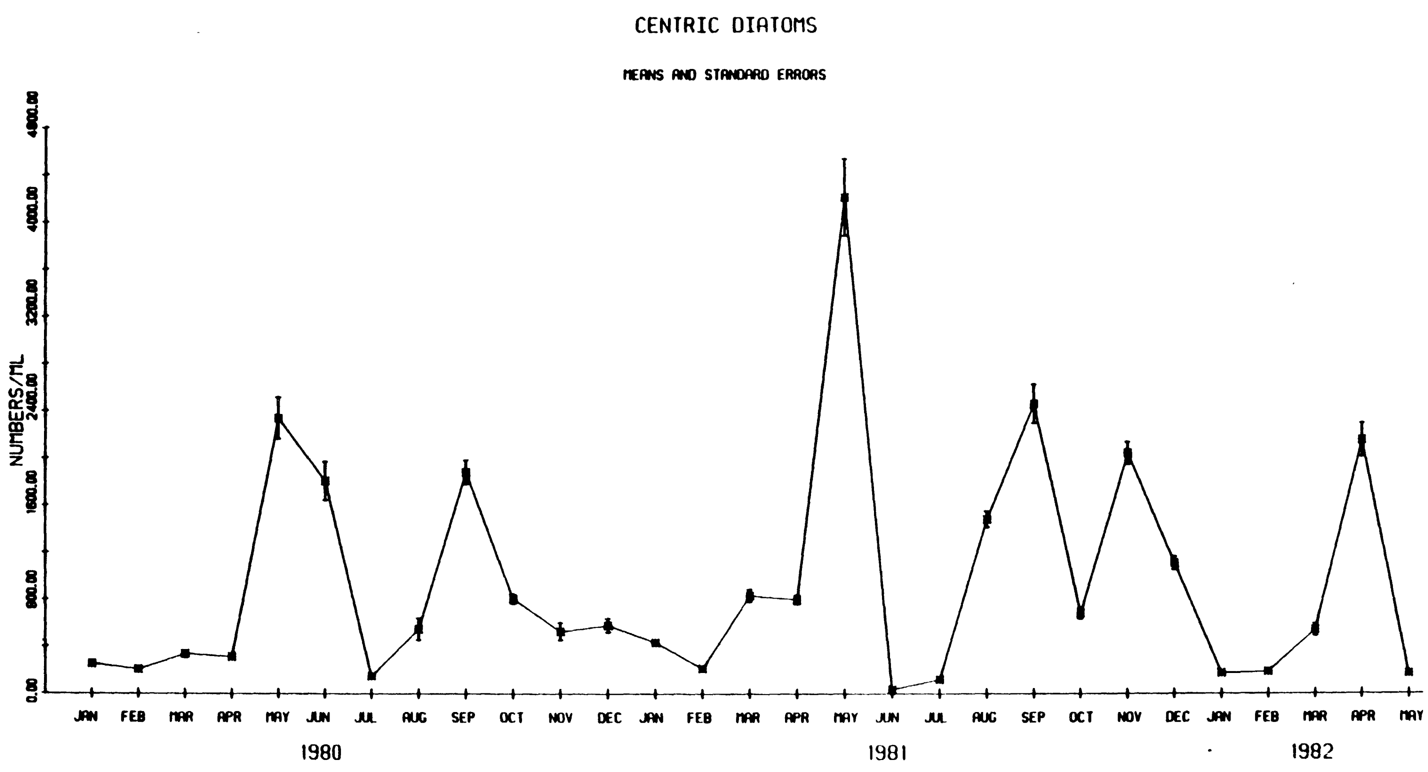

FIG. 8. Variation of centric diatom numbers during 1980, 1981, and 1982.

Table 9. Monthly variation of pennate diatoms from 1975 through May 1982 (cells/mL).

Month	1975'	1976'	1977'	1978'	1979'	1980'	1981'	1982'
January		991.(186.)		598.(79.0)	213.(16.4)	605.(54.0)	290.(19.1)	620.(50.5)
February	1,640.(196.)	265.(43.0)		62.2(8.27)	43.8(4.30)	153.(16.0)	104.(9.70)	378.(34.5)
March	1,340.(146.)	329.(46.3)	1,210.(90.6)	41.7(4.68)	200.(17.9)	222.(26.8)	529.(50.1)	843.(129.)
April	1,160.(306.)	1,340.(123.)	1,710.(187.)	226.(37.1)	748.(67.9)	376.(24.7)	1,650.(118.)	1,150.(145.)
May	3,040.(278.)	864.(158.)	383.(45.0)	1,910.(162.)	2,490.(142.)	2,870.(215.)	4,540.(526.)	1,250.(225.)
June	1,220.(102.)	332.(29.9)	743.(129.)	1,750.(134.)		2,020.(209.)	268.(35.6)	
July	90.8(12.8)	2,900.(459.)	487.(44.8)	1,450.(160.)	156.(26.7)	284.(44.0)	223.(43.5)	
August	84.8(16.8)	1,250.(207.)	73.2(10.1)	514.1(17.2)	267.(37.2)	68.7(14.4)	97.8(15.0)	
September	270.(52.7)	1,920.(411.)	146.(15.5)	120.(23.2)	133.(25.6)	326.(31.6)	772.(45.4)	
October	295.(34.6)	498.(36.6)	822.(45.2)	570.(63.1)	381.(22.8)	1,390.(131.)	358.(43.4)	
November	501.(74.2)	842.(100.)	724.(100.)	963.(107.)	638.(57.0)	1,570.(231.)	1,170.(105.)	
December	333.(43.4)	1,320.(148.)	548.(50.2)	572.(45.5)	1,760.(131.)	810.(84.5)	1,280.(131.)	
Yearly Mean	907.(271.)	1,070.(220.)	685.(155.)	731.(74.6)	639.(236.)	891.(255.)	940.(359.)	849.(162.)

'Mean is followed by the standard error.

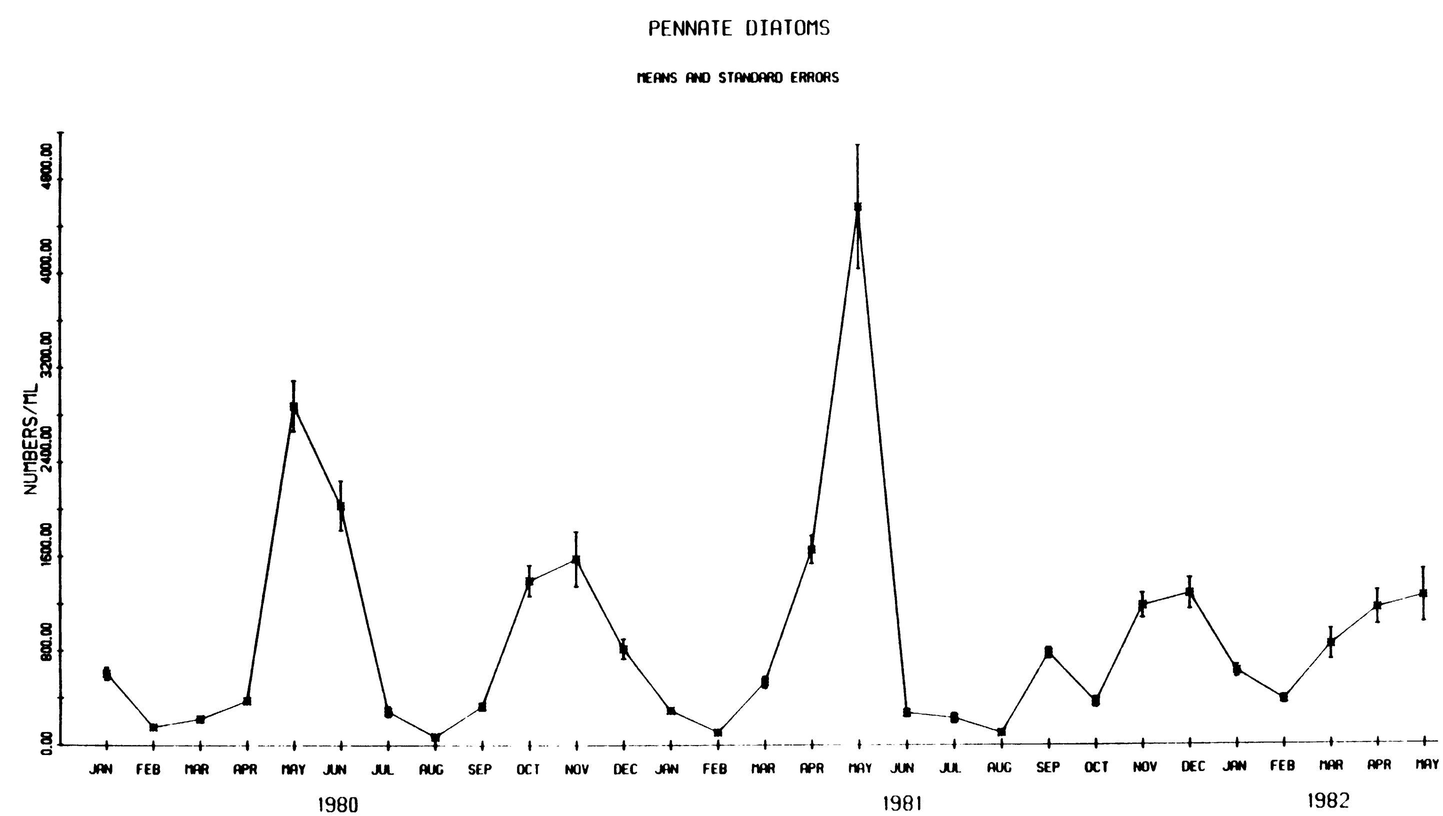

FIG. 9. Variation of pennate diatom numbers during 1980, 1981, and 1982.

through October. Highest density occurred in May 1981, dropped sharply, and remained low until thermal stratification ceased in the fall.

Desmids were consistently low in abundance through 1982 (Table 10 and Fig. 10). Maximum population density of 5 cells/mL was obtained in May 1981. No significant change in population was found from 1975 to 1982.

The group of "other algae" is composed of phytoplankton which cannot be adequately placed in any of the groups mentioned above. Most algae in this group are green algae. In 1980-81, this group of phytoplankton reached peaks of abundance in September 1980 and April 1981 (Table 11 and Fig. 11). The 1979 mean population density was the lowest in the period from 1975 through 1982. 1981 had the highest mean population density.

In 1980 and 1981, total phytoplankton abundance reached peaks in May, September, and November (Table 12 and Fig. 12). In both years, the maximum occurred in May and corresponded with maximums of centric and pennate diatoms, respectively. A maximum occurred in April 1982. High population peaks were also encountered in September, October, and November 1980 and 1981, after isothermal conditions resumed. The mean abundances for 1980 and 1981 were the highest since 1976.

Monthly Variations of Phytoplankton Community Structure

Occurrences of Dominant and Co-dominant Forms --

For this report, any form constituting 10% or more of the total population in a sample was considered dominant. A comparison of these monthly frequencies for the years in which the plant has been in operation can reveal any change which has occurred in the distribution of these species during the period. Those forms which appeared relatively infrequently (less than 50% of the total

Table 10. Monthly variation of desmids from 1975 through May 1982 (cells/mL).

Month	1975[1]	1976[1]	1977[1]	1978[1]	1979[1]	1980[1]	1981[1]	1982[1]
January	0.0(0.0)			1.05(.640)	0.461(0.155)	1.46(0.37)	.944(.094)	.228(.113)
February	0.8(0.5)	.238(.191)		.275(.207)	0.339(0.120)	0.133(0.072)	.339(.117)	.550(.189)
March	0.8(0.5)	.417(.298)	.142(.142)	.208(.215)	0.322(0.140)	1.10(0.306)	.417(.298)	.278(.201)
April	1.2(1.2)	.825(.592)	.275(.275)	0.0(0.0)	0.0(0.0)	0.606(0.23)	1.39(.399)	.183(.183)
May	3.0(0.0)	1.65(.642)	1.52(.583)	0.83(0.44)	2.75(1.06)	1.10(0.805)	5.53(2.56)	2.49(.632)
June	2.5(0.9)	.142(.142)	1.25(.580)	0.83(0.43)		2.20(0.938)	.133(.090)	
July	2.2(1.2)	1.25(.843)	1.47(.325)	2.22(0.70)	0.833(0.308)	1.60(0.387)	.692(.379)	
August	0.4(0.2)	.550(.371)	1.11(.587)	0.51(0.22)	0.278(0.166)	0.594(0.41)	.183(.183)	
September	0.3(0.3)	.275(.275)	.0667(.0667)	0.022(0.022)	0.231(0.115)	0.839(0.337)	.183(.183)	
October	0.8(0.4)	0.0(0.0)	0.0(0.0)	1.20(0.439)	0.511(0.225)	0.550(0.298)	0.0(0.0)	
November	0.5(0.3)	0.0(0.0)	.825(.431)	1.94(0.561)	1.11(0.424)	0.558(0.313)	.275(.275)	
December	0.0(0.0)	.447(.298)	1.38(.604)	1.98(0.397)	1.25(0.506)	1.10(0.74)	.550(.298)	
Yearly Mean	1.14(.298)	.484(.150)	.804(.197)	0.935(0.329)	0.731(0.233)	0.987(0.164)	.877(.437)	.746(.441)

[1]Mean is followed by the standard error.

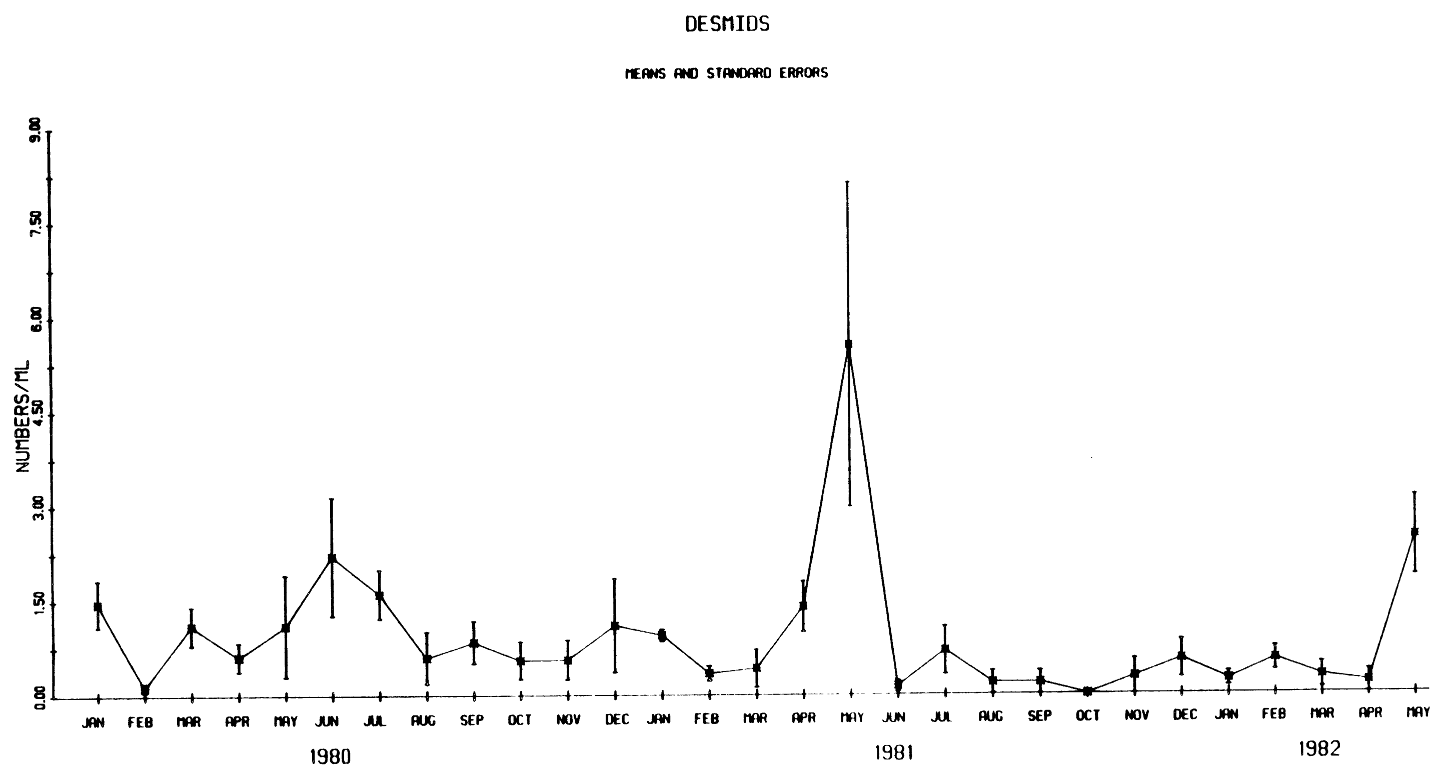

FIG. 10. Variation of desmid numbers during 1980, 1981, and 1982.

Table 11. Monthly variation of other algae from 1975 through May 1982 (cells/mL).

Month	1975'	1976'	1977'	1978'	1979'	1980'	1981'	1982'
January	62.4(18.1)			50.8(11.2)	84.4(9.25)	64.4(13.2)	54.2(5.61)	23.4(4.33).
February	7.0(3.2)	58.3(30.4)		53.9(8.07)	94.4(9.4)	76.9(11.6)	186.(21.5)	182.(52.8)
March	29.4(4.4)	39.9(5.93)	16.7(5.49)	66.2(7.79)	92.0(13.9)	92.2(12.7)	81.7(29.6)	182.(39.0)
April	70.0(16.9)	91.1(42.8)	167.(20.8)	57.6(10.9)	29.8(6.58)	46.9(6.30)	503.(117.)	106.(29.3)
May	84.0(17.2)	148.(27.8)	55.6(10.5)	104.(11.3)	111.(30.5)	106.(18.6)	222.(57.5)	152.(23.2)
June	148.(29.0)	104.(12.1)	37.9(7.65)	400.(44.3)		204.(32.8)	30.2(4.03)	
July	480.(57.1)	361.(52.3)	193.(22.0)	514.(63.9)	40.8(6.97)	200.(25.2)	110.(17.4)	
August	55.0(22.1)	192.(19.8)	206.(26.7)	119.(23.4)	114.(11.7)	333.(54.0)	123.(16.8)	
September	31.6(6.2)	481.(54.7)	62.0(7.15)	86.6(10.3)	91.(10.6)	399.(61.0)	269.(32.8)	
October	44.0(5.0)	166.(23.7)	183.(21.4)	245.(23.7)	179.(18.4)	149.(15.4)	141.(14.4)	
November	65.7(13.0)	84.7(14.5)	119.(15.6)	112.(18.5)	93.3(9.22)	152.(42.2)	145.(21.2)	
December	71.0(13.1)	42.0(7.67)	63.4(15.1)	124.(13.0)	96.9(10.5)	66.6(15.9)	84.9(12.6)	
Yearly Mean	98.7(39.7)	153.(39.5)	110.(22.6)	161.(20.3)	93.3(11.7)	157.(32.0)	162.(36.7)	129.(29.9)

'Mean is followed by the standard error.

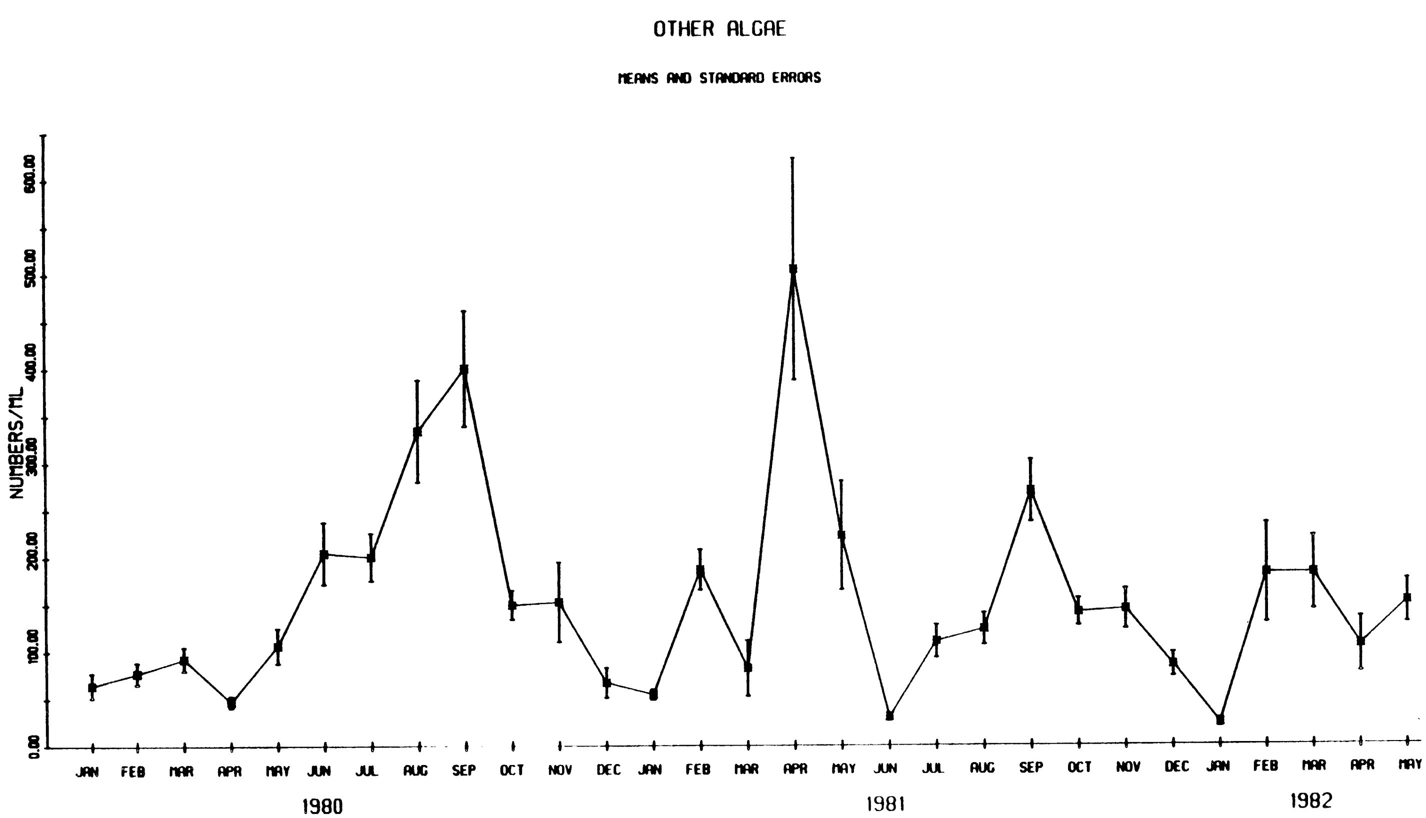

FIG. 11. Variation of other algae numbers during 1980, 1981, and 1982.

Table 12. Monthly variation of total algae from 1975 through May 1982 (cells/mL).

Month	1975[1]	1976[1]	1977[1]	1978[1]	1979[1]	1980[1]	1981[1]	1982[1]
January	3,530.(429.)			1,490.(210.)	1,090.(92.5)	1,950.(195.)	1,410.(106.)	1,210.(58.9)
February	2,970.(318.)	1,410.(147.)		465.(81.7)	691.(62.9)	833.(57.3)	1,110.(76.5)	1,610.(137.)
March	3,340.(421.)	1,840.(182.)	2,500.(206.)	681.(63.9)	1,330.(121.)	1,100.(90.2)	2,540.(172.)	2,600.(226.)
April	5,020.(816.)	2,990.(200.)	3,890.(336.)	1,500.(170.)	3,850.(243.)	1,690.(86.5)	3,870.(238.)	4,500.(316.)
May	5,800.(413.)	4,520.(396.)	1,860.(214.)	4,840.(397.)	3,970.(224.)	5,980.(372.)	11,000.(1055.)	2,360.(284.)
June	3,710.(302.)	1,550.(132.)	1,650.(249.)	7,220.(461.)		5,030.(352.)	2,790.(214.)	
July	4,200.(243.)	7,940.(836.)	2,280.(156.)	3,880.(321.)	1,190.(92.3)	2,240.(180.)	1,860.(154.)	
August	1,270.(92.8)	3,140.(292.)	2,170.(296.)	1,460.(172.)	1,260.(82.0)	3,430.(409.)	3,200.(201.)	
September	2,380.(208.)	5,050.(675.)	1,690.(140.)	1,350.(113.)	1,730.(198.)	4,680.(338.)	7,260.(538.)	
October	2,490.(286.)	2,720.(291.)	2,680.(285.)	4,530.(450.)	2,780.(157.)	4,620.(358.)	3,100.(256.)	
November	2,150.(259.)	3,090.(237.)	3,210.(428.)	3,580.(407.)	2,550.(150.)	4,340.(464.)	4,700.(193.)	
December	2,790.(170.)	2,870.(312.)	1,840.(189.)	5,060.(414.)	4,150.(308.)	2,920.(390.)	3,510.(264.)	
Yearly Mean	3,280.(399.)	3,390.(519.)	2,380.(228.)	3,000.(272.)	2,240.(387.)	3,240.(488.)	3,860.(802.)	2,460.(570.)

[1]Mean is followed by the standard error.

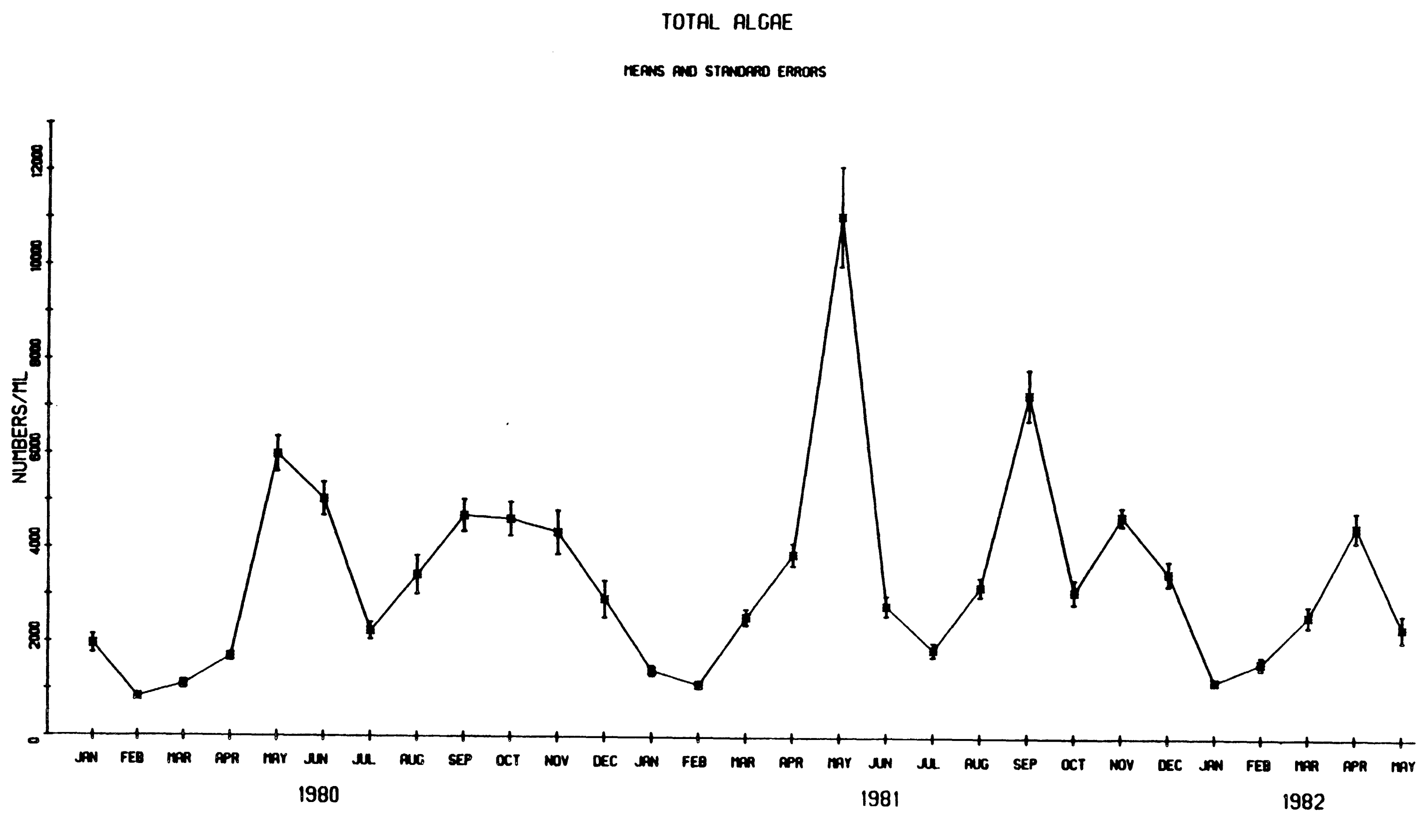

FIG. 12. Variation of total algae numbers during 1980, 1981, and 1982.

monthly samples) as dominant forms were excluded from consideration. If they were included, the resulting complexity could obscure the existing patterns. The monthly comparisons among the years were made for March to December, when complete data from 1975 to 1982 were available. Data for 1982 were complete for January through May. No samples were collected after May.

In March, Tabellaria fenestrata v. intermedia and centric diatoms were dominant in 1975; Cyclotella stelligera and flagellates were dominant in 1976; flagellates, Fragilaria crotonensis, and Synedra filiformis were dominant in 1977; Stephanodiscus sp. was dominant in 1978; flagellates were dominant in 1979; flagellates were dominant in 1980; flagellates and chrysophycean flagellates in 1981; and flagellates, Fragilaria crotonensis, chrysophycean flagellates, and Stephanodiscus subtilis in 1982 (Table 13). During April, the dominant forms were flagellates and Cyclotella stelligera in 1975; Fragilaria crotonensis and Asterionella formosa in 1976; flagellates, Fragilaria crotonensis, chrysophycean flagellates, and Synedra filiformis in 1977; chrysophycean flagellates and Stephanodiscus sp. in 1978; Stephanodiscus minutus in 1979; flagellates and Asterionella formosa in 1980; Asterionella formosa in 1981; and chrysophycean flagellates, centric diatoms, and Stephanodiscus subtilis in 1982 (Table 14). The dominant forms for May were Tabellaria fenestrata v. intermedia in 1975, flagellates in 1976, flagellates in 1977, Melosira granulata in 1978, and flagellates and Asterionella formosa in 1979; Asterionella formosa and Melosira granulata in 1980; Stephanodiscus subtilis in 1981; and chrysophycean flagellates, Fragilaria crotonensis, and Tabellaria fenestrata v. intermedia in 1982 (Table 15). In June, the dominant forms were flagellates and Tabellaria fenestrata v. intermedia in 1975, flagellates and Dinobryon divergens in 1976, Fragilaria crotonensis in 1977, and chrysophycean flagellates in 1978

Table 13. Occurrence of dominant forms in March 1975, 1976, 1977, 1978, 1979, 1980, 1981, and 1982.

	Occurrences							
Form	1975	1976	1977	1978	1979	1980	1981	1982
Anacystis incerta	0	5	0	2	7	3	0	0
Cyclotella stelligera	4	6	0	0	0	0	0	0
Flagellates	1	9	9	3	18	15	9	14
Gomphosphaeria lacustris	2	3	2	0	3	1	0	0
Cyclotella sp.	0	3	0	0	0		0	0
Asterionella formosa	0	1	0	0	0	0	1	0
Blue-green, unknown cells	0	1	0	0	0	0	0	0
Tabellaria fenestrata var. intermedia	9	0	0	0	0	1	0	1
Centric diatoms, unknown	6	0	0	4	0	5	3	1
Stephanodiscus sp.	3	0	0	11	0	5	1	0
Fragilaria crotonensis	1	0	11	0	1	6	0	9
Chrysophycean flagellate sp.	0	0	2	0	6	2	11	15
Synedra filiformis	0	0	11	0	0	0	0	0
Stephanodiscus #5	0	0	0	5	0	0	0	0
Stephanodiscus minutus	0	0	0	0	3	1	1	1
Stephanodiscus subtilis	0	0	0	0	0	0	3	12
Unknown colony sp. A	0	0	0	0	0	0	0	3
Stephanodiscus hantzschii	0	0	0	0	0	2	0	0
Anacystis cyanea	0	0	0	0	0	1	0	0
Number of samples	9	12	12	12	18	18	12	18

Table 14. Occurrence of dominant forms in April 1975, 1976, 1977, 1978, 1979, 1980, 1981, and 1982.

Form	Occurrences 1975	1976	1977	1978	1979	1980	1981	1982
Cyclotella stelligera	5	1	0	0	0	0	0	0
Flagellates	6	0	6	5	1	18	2	4
Fragilaria crotonensis	1	6	9	0	0	1		7
Gomphosphaeria lacustris	1	0	0	0	0	1	0	0
Stephanodiscus minutus	1	0	0	0	12	0	0	0
Stephanodiscus tenuis	2	0	0	0	0	0	0	0
Stephanodiscus #5	0	0	0	3	0	0	0	0
Stephanodiscus sp.	0	0	0	10	4	0	0	2
Anacystis incerta	1	3	1	3	0	2	0	0
Asterionella formosa	0	12	0	0	5	9	11	0
Rhizosolenia gracilis	0	3	0	0	0	0	0	0
Green colony, unknown	0	1	0	0	0	0	0	0
Fragilaria intermedia v. fallax	0	1	0	0	0	0	0	0
Chrysophycean flagellate sp.	0	0	6	9	0	7	3	16
Synedra filiformis	0	0	11	0	0			
Synedra ostenfeldii	0	0	1	0	0	0	1	0
Unknown colony sp. A	0	0	0	0	0	0	4	0
Centric diatoms, unknown	0	0	0	0	0	0	0	14
Stephanodiscus hantzschii	0	0	0	0	0	0	0	1
Stephanodiscus subtilis	0	0	0	0	0	0	0	11
Tabellaria fenestrata v. intermedia	0	0	0	0	0	0	0	3
Number of samples	9	12	12	12	12	18	12	18

Table 15. Occurrence of dominant forms in May 1975, 1976, 1977, 1978, 1979, 1980, 1981, and 1982.

	Occurrences							
Form	1975	1976	1977	1978	1979	1980	1981	1982
Anacystis incerta	4	0	0	0	1	0	0	0
Fragilaria crotonensis	4	0	2	4	1	2	1	15
Tabellaria fenestrata var. *intermedia*	5	0	1	0	0	0	0	17
Flagellates	4	11	9	1	9	6	5	6
Ochromonas sp.	0	5	0	0	0	0	0	0
Centric diatom, unknown	0	1	0	0	0	0	0	0
Oscillatoria limnetica	0	1	0	0	0	0	0	0
Rhizosolenia gracilis	0	1	0	0	0	0	0	0
Cyclotella sp.	0	1	0	0	0	0	0	0
Asterionella formosa	0	1	0	3	12	18	0	0
Stephanodiscus subtilis	0	1	0	0	0	0	11	0
Stephanodiscus sp.	0	0	0	1	0	0	1	0
Gomphosphaeria lacustris	0	0	1	0	0	0	0	0
Chrysophycean flagellate sp.	0	0	5	1	0	0	1	17
Synura sp.	0	0	1	0	0	0	0	0
Melosira granulata	0	0	0	6	0	18	0	0
Synedra ostenfeldii	0	0	0	0	8	0	0	0
Unknown colony sp. A	0	0	0	0	0	0	0	2
Synedra filiformis	0	0	0	0	0	5	0	0
Number of samples	9	12	12	12	12	18	12	18

(Table 16). Because no sample was collected in June 1979, there was no information on dominant forms available for this month. The dominant forms in June were Fragilaria crotonensis and Melosira granulata in 1980; and chrysophycean flagellates in 1981. In July, Cyclotella stelligera, Dictyosphaerium pulchellum, and Gloeocystis sp. were dominant in 1975; no forms were dominant in more than 50% of the total samples in 1976; Cyclotella sp., Cyclotella comensis, and Fragilaria crotonensis were dominant in 1977; Fragilaria crotonensis and Scenedesmus bicellularis were dominant in 1978; and flagellates, Fragilaria crotonensis, chrysophycean flagellates, and Anabaena flos-aquae were dominant in 1979; chrysophycean flagellates, flagellates, and Oocystis sp. in 1980; chrysophycean flagellates and flagellates in 1981 (Table 17). In August, Anacystis incerta and Chromulina parvula were dominant in 1975; Fragilaria crotonensis was dominant in 1976; Anacystis incerta and flagellates were dominant in 1977; Fragilaria crotonensis was dominant in 1978; Fragilaria crotonensis and Anacystis incerta were dominant in 1979; Anacystis incerta and flagellates in 1980; and flagellates, chrysophycean flagellates, and Cyclotella comensis in 1981 (Table 18). In September, Anacystis incerta and flagellates predominated in 1975; Fragilaria crotonensis did so in 1976; Anacystis incerta and flagellates did so in 1977; Anacystis incerta did so in 1978; Anacystis incerta, flagellates, and Melosira granulata did so in 1979; Anacystis incerta and Melosira granulata in 1980; and Anacystis incerta and Cyclotella sp. #6 in 1981 (Table 19). In October, Anacystis incerta, flagellates, and Gomphosphaeria lacustris were dominant in 1975; flagellates were dominant in 1976; Anacystis incerta, Fragilaria crotonensis, and flagellates were dominant in 1977; Anacystis incerta, Gomphosphaeria lacustris, and Melosira granulata were dominant in 1978; Anacystis incerta and Gomphosphaeria lacustris were dominant in 1979;

Table 16. Occurrence of dominant forms in June 1975, 1976, 1977, 1978, 1979, 1980, and 1981.

	Occurrences						
Form	1975	1976	1977	1978	1979	1980	1981
Flagellates	9	11	2	0	-	2	5
Tabellaria fenestrata var. intermedia	10	0	5	0	-	0	0
Fragilaria capucina	1	0	0	0	-	0	0
Stephanodiscus tenuis	2	0	0	0	-	0	0
Oscillatoria limnetica	2	0	0	0	-	0	0
Anacystis incerta	1	0	1	2	-	1	0
Gomphosphaeria lacustris	2	1	1	2	-	2	0
Fragilaria crotonensis	2	0	8	1	-	6	0
Chlorella sp.	0	1	0	0	-	0	0
Diatoma tenue var. elongatum	0	1	0	0	-	0	0
Dinobryon bavaricum	0	5	0	0	-	0	0
Dinobryon divergens	0	9	0	0	-	0	0
Chrysophycean flagellate sp.	0	0	2	12	-	0	12
Merismopedia elegans	0	0	1	0	-	0	0
Cyclotella stelligera	0	0	1	0	-	0	0
Asterionella formosa	0	0	0	0	0	-	0
Blue-green colony, unknown	0	0	0	0	0	-	0
Melosira granulata	0	0	0	0	0	-	0
Number of samples	12	12	12	12	-	12	12

Table 17. Occurrence of dominant forms in July 1975, 1976, 1977, 1978, 1979, 1980, and 1981.

Form	Occurrences						
	1975	1976	1977	1978	1979	1980	1981
Anabaena flos-aquae	0	0	0	0	8	3	1
Anacystis incerta	2	0	0	3	2	3	0
Cyclotella sp.	2	0	8	0	0	0	0
Cyclotella stelligera	9	0	0	0	0	0	0
Chrysophycean flagellate sp.	0	0	0	0	11	8	11
Dictyosphaerium pulchellum	10	0	0	0	0	0	0
Gloeocystis sp.	9	1	0	0	0	0	0
Merismopedia tennuissima	1	0	0	0	0	0	0
Gomphosphaeria lacustris	1	0	1	2	4	3	1
Flagellates	4	0	3	5	10	7	9
Green coccoid, unknown	1	0	0	0	0	0	0
Gloeocystis planctonica	1	0	0	1	0	0	3
Stephanodiscus sp.	0	1	0	0	0	0	0
Centric diatom, unknown	0	5	0	0	0	0	0
Melosira granulata	0	0	0	1	0	0	0
Fragilaria crotonensis	0	5	10	11	6	4	3
Sphaerocystis sp.	0	1	0	0	0	0	0
Tabellaria fenestrata var. _intermedia_	0	0	0	2	0	0	0
Stephanodiscus subtilis	0	1	0	0	0	0	0
Cyclotella comensis	0	0	12	0	0	0	0
Scenedesmus bicellularis	0	0	0	6	0	0	0
Green colony, unknown	0	0	0	0	0	0	3
Agmenellum quadruplicatum	0	0	0	0	0	0	1
Green cells, unknown	0	0	0	0	0	2	0
Oocystis sp.	0	0	0	0	0	8	0
Number of samples	12	12	12	18	12	12	12

Table 18. Occurrence of dominant forms in August 1975, 1976, 1977, 1978, 1979, 1980, and 1981.

Form	Occurrences						
	1975	1976	1977	1978	1979	1980	1981
Anacystis incerta	8	3	10	3	15	17	5
Anacystis cyanea	0	0	0	1	1	0	0
Anacystis thermalis	0	0	5	0	0	1	2
Anabaena flos-aquae	0	0	0	6	0	0	0
Agmenellum quadruplicatum	0	0	0	0	1	0	0
Chromulina parvula	9	0	0	0	0	0	0
Gomphosphaeria lacustris	3	2	0	3	5	6	1
Cyclotella stelligera	4	0	0	0	0	0	0
Gloeocystis sp.	5	4	0	0	0	0	0
Flagellates	3	5	6	4	8	9	9
Synura sp.	1	0	0	0	0	0	0
Fragilaria crotonensis	0	11	0	18	14	0	0
Gloeocystis planctonica	0	1	0	1	0	0	0
Chrysophycean flagellate sp.	0	1	5	0	1	1	13
Tabellaria fenestrata var. *intermedia*	0	0	0	1	0	0	0
Crucigenia rectangularis	0	0	4	0	0	0	0
Dinobryon divergens	0	0	0	0	1	0	0
Cyclotella sp.	0	0	1	0	0	0	0
Green cells, undetermined	0	0	0	0	1	0	0
Green colony, unknown	0	0	0	0	3	3	0
Cyclotella comensis	0	0	0	0	0	0	18
Green cells, unknown	0	0	0	0	0	1	0
Green coccoid, unknown	0	0	0	0	0	1	0
Melosira granulata	0	0	0	0	0	7	0
Number of samples	12	12	12	18	18	18	18

Table 19. Occurrence of dominant forms in September 1975, 1976, 1977, 1978, 1979, 1980, and 1981.

Form	Occurrences						
	1975	1976	1977	1978	1979	1980	1981
Anabaena flos-aquae	0	0	0	0	1	0	0
Anacystis incerta	11	4	12	18	16	13	15
Fragilaria crotonensis	2	8	0	0	0	0	0
Gomphosphaeria lacustris	5	0	2	1	4	1	1
Flagellates	6	1	6	1	9	6	6
Anacystis thermalis	4	0	0	0	1	0	0
Melosira granulata	0	0	0	8	8	15	0
Ochromonas sp.	2	0	0	0	0	0	0
Gloeocystis sp.	0	5	0	0	0	0	0
Botryococcus braunii	0	0	0	1	0	0	0
Sphaerocystis sp.	0	1	0	0	0	0	0
Gloeocystis planctonica	0	0	0	1	0	0	0
Chrysophycean flagellate sp.	0	1	0	0	1	0	7
Anacystis cyanea	0	0	0	1	0	0	0
Cyclotella sp. #6	0	0	0	0	0	0	16
Cyclotella comensis	0	0	0	0	0	6	4
Agmenellum quadruplicatum	0	0	0	0	0	1	0
Green colony, unknown	0	0	0	0	0	1	0
Tabellaria fenestrata var. *intermedia*	0	0	0	0	0	1	0
Number of samples	12	12	12	18	16	18	18

Anacystis incerta and Tabellaria fenestrata v. intermedia in 1980; and flagellates and chrysophycean flagellates in 1981 (Table 20). During November, the dominant forms were flagellates, Anacystis incerta, Fragilaria crotonensis, and Cyclotella comensis in 1975; flagellates and Cyclotella sp. in 1976; flagellates, Anacystis incerta, and Gomphosphaeria lacustris in 1977; Anacystis incerta, Fragilaria crotonensis, and Gomphosphaeria lacustris in 1978; flagellates, Anacystis incerta, and Gomphosphaeria lacustris in 1979; Anacystis incerta and Tabellaria fenestrata v. intermedia in 1980; and flagellates and Stephanodiscus subtilis in 1981 (Table 21). In the month of December, centric diatoms and Cyclotella stelligera were dominant in 1975; Fragilaria crotonensis and flagellates were dominant in 1976; Anacystis incerta, Gomphosphaeria lacustris, and Tabellaria fenestrata v. intermedia were dominant in 1977; Gomphosphaeria lacustris and Anacystis incerta were dominant in 1978; Anacystis incerta and Fragilaria crotonensis were dominant in 1979; Anacystis incerta and Tabellaria fenestrata v. intermedia in 1980; and Fragilaria crotonensis, flagellates, and Stephanodiscus subtilis in 1981 (Table 22).

No consistent trend of change in dominant species was observed in the monthly comparisons during the years 1975 through 1982. However, if the data are tabulated for those diatoms which are associated with an identifiable trophic level (Table 23), certain patterns of total annual occurrence for the dominant diatom species emerge (Table 24). These patterns are summarized in Table 25. The occurrences of mesotrophic species not tolerant of nutrient enrichment continuously decrease from 34 in 1975 to 0 in 1982. On the other hand, there has been an increase from 47 in 1975 to 79 in 1982 in the occurrences of mesotrophic species which are tolerant of moderate nutrient enrichment. The highest numbers of occurrences were in 1977 and 1980-82. The highest

Table 20. Occurrence of dominant forms in October 1975, 1976, 1977, 1978, 1979, 1980, and 1981.

Form	Occurrences 1975	1976	1977	1978	1979	1980	1981
Agmenellum quadruplicatum	0	0	0	0	1	0	0
Anacystis incerta	10	5	10	16	15	15	1
Fragilaria crotonensis	1	2	10	0	0	4	1
Flagellates	8	9	8	0	0	0	11
Gomphosphaeria lacustris	6	2	3	13	9	6	5
Ochromonas sp.	3	0	0	0	0	0	0
Gomphosphaeria sp.	0	0	0	1	0	0	0
Cyclotella comensis	0	2	0	0	0	5	1
Gloeocystis planctonica	0	1	0	0	0	0	0
Melosira granulata	0	0	0	13	5	0	0
Chrysophycean flagellate sp.	0	2	0	0	0	0	6
Gloeocystis sp.	0	1	1	0	0	0	0
Anacystis cyanea	0	0	1	0	0	0	0
Tabellaria fenestrata var. intermedia	0	0	1	0	0	16	0
Cyclotella sp. #6	0	0	0	0	0	0	4
Anacystis thermalis	0	0	0	0	0	1	0
Green colony, unknown	0	0	0	0	0	1	0
Number of samples	10	12	12	18	18	18	12

Table 21. Occurrence of dominant forms in November 1975, 1976, 1977, 1978, 1979, 1980, and 1981.

	Occurrences						
Form	1975	1976	1977	1978	1979	1980	1981
Flagellates	7	8	9	0	11	0	7
Anacystis incerta	7	5	10	11	10	11	3
Chrysophycean flagellate sp.	0	3	3	0	0	0	3
Fragilaria crotonensis	6	4	4	7	6	4	3
Agmenellum quadruplicatum	1	0	1	1	1	0	0
Gomphosphaeria lacustris	4	0	8	9	5	3	1
Centric diatom, unknown	2	0	0	0	0	0	2
Stephanodiscus sp.	1	0	0	0	0	0	1
Stephanodiscus minutus	0	0	0	0	0	0	1
Stephanodiscus subtilis	0	0	0	0	0	0	12
Cyclotella comensis	10	0	0	0	0	0	0
Cyclotella sp.	0	7	0	0	0	0	0
Tabellaria fenestrata var. *intermedia*	0	1	0	0	0	8	0
Asterionella formosa	0	2	2	0	0	3	0
Gloeocystis sp.	0	1	0	0	0	0	0
Anacystis thermalis	0	0	0	0	2	2	0
Number of samples	12	12	12	12	12	12	12

Table 22. Occurrence of dominant forms in December 1975, 1976, 1977, 1978, 1979, 1980, and 1981.

Form	Occurrences						
	1975	1976	1977	1978	1979	1980	1981
Asterionella formosa	0	0	0	0	5	0	0
Centric diatom, unknown	9	0	0	0	0	2	4
Cyclotella stelligera	9	0	0	0	0	0	0
Ochromonas sp.	3	0	0	0	0	0	0
Sphaerocystis schroeteri	1	0	0	0	0	0	0
Gomphosphaeria lacustris	1	1	7	17	5	3	2
Stephanodiscus minutus	1	0	0	0	0	0	0
Stephanodiscus sp.	1	0	0	0	0	0	0
Cyclotella comensis	1	1	0	0	0	0	0
Cyclotella sp.	1	0	0	0	0	0	0
Anacystis incerta	1	3	12	16	6	11	2
Fragilaria crotonensis	0	12	0	0	11	0	10
Flagellates	0	6	0	2	1	0	13
Fragilaria capucina var. lanceolata	0	1	0	0	0	0	4
Anabaena flos-aquae	0	1	1	0	0	0	0
Gloeocystis planctonica	0	2	0	0	0	0	0
Tabellaria fenestrata var. intermedia	0	0	6	0	0	10	0
Agmenellum quadruplicatum	0	0	1	1	0	0	0
Anacystis thermalis	0	0	2	0	0	2	0
Microcystis sp.	0	0	0	0	0	0	1
Stephanodiscus subtilis	0	0	0	0	0	0	17
Chrysophycean flagellates sp.	0	0	0	0	0	0	5
Melosira granulata	0	0	0	0	0	1	0
Number of samples	11	12	12	18	12	12	18

Table 23. Apparent trophic preference and abundance of selected diatoms in Lake Michigan.[1]

Selected Diatoms	Trophic Preference O	M1	M2	E	EI
Cyclotella comta (Ehr.) Kütz.	P	M	P		
Cyclotella operculata (Ag.) Kütz.	M				
Cyclotella ocellata Pant.	M	P			
Cyclotella kuetzingiana Thwaites	P	M	P		
Cyclotella stelligera Cl. n. Grun.	P	M	P		
Melosira distans (Ehr.) Kütz.	M				
Melosira distans var. alpigena Grun.					M
Melosira islandica O. Mull.	P	M	P		
Tabellaria fenestrata (Lyngb.) Kütz.		P	M	P	
Tabellaria flocculosa (Roth) Kütz.		M	P		
Rhizosolenia eriensis H. L. Smith	P	M	P		
Stephanodiscus transilvanicus Pant.	P	M			
Synedra ulna var. chaseana Thomas	P	M			
Cyclotella michiganiana Skv.	P	M	P		
Asterionella formosa Hass.		P	M	P	
Fragilaria crotonensis Kitton		P	M	P	
Stephanodiscus alpinus Hust. ex Huber-Pestalozzi		P	M	P	
Stephanodiscus minutus Grun. ex Cleve and Moll.				P	M
Stephanodiscus niagarae Ehr.			P	M	
Stephanodiscus hantzschii Grun.			P	M	

(continued)

Symbols: O, oligotrophic; M1, mesotrophic but intolerant of nutrient enrichment; M2, mesotrophic and tolerant of moderate nutrient enrichment; E, eutrophic; EI, recently introduced eutrophic species; P, presence of species; and M, apparent maximum abundance of the species.

References: Holland (1968, 1969); Stoermer and Yang (1969, 1970); Holland and Beeton (1972). (Courtesy to Tarapchak and Stoermer).

[1]Tarapchak and Stoermer (1976).

Table 23. (Concluded).

Selected Diatoms	Trophic Preference O	M1	M2	E	EI
Synedra delicatissima Lewis		P	M	P	
Synedra ulna v. *danica* (Kütz.) Grun.		P	M	P	
Synedra ostenfeldii (Krieger) A. Cleve		P	M	P	
Synedra filiformis Grun.		P	M	P	
Amphipleura pellucida (Kütz.)			P	M	P
Melosira granulata (Ehr.) Ralfs			P	M	
Melosira granulata var. *angustissima* Mull.			P	M	
Fragilaria capucina Desm.			P	M	
Fragilaria capucina var. *mesolepta* (Rabh.) Grunow			P	M	
Fragilaria construens (Ehr.) Grunow			P	M	
Fragilaria intermedia Grun.			P	M	
Stephanodiscus tenuis Hust.				P	M
Asterionella bleakeleyi Wm. Smith				P	M
Diatoma tenue v. *elongatum* Lyng.				P	M
Stephanodiscus binderanus (Kütz.) Krieger				P	M
Stephanodiscus subtilis (Van Goor) A. Cleve				P	M
Nitzschia dissipata (Kütz.) Grun.				M	P
Coscinodiscus subsalsa Juhl.-Dannf.					M

Table 24. The annual occurrence of selected dominant diatom forms in 1975, 1976, 1977, 1978, 1979, 1980, 1981, and 1982 (5 months). (See Table 23 for definition of symbols M1, M2, and E).

	1975	1976	1977	1978	1979	1980	1981	1982
Stephanodiscus minutus (E)	2	8	0	0	17	3	11	0
Fragilaria capucina (E)	2	1	0	0	0	0	4	0
Stephanodiscus tenuis (E)	4	1	0	0	0	0	0	0
Stephanodiscus subtilis (E)	0	2	0	0	0	0	43	11
Diatoma tenue v. *elongatum* (E)	0	1	0	0	0	0	0	0
Fragilaria crotonensis (M2)	17	52	54	48	40	48	18	58
Tabellaria fenestrata var. *intermedia* (M2)	30	1	16	6	0	38	43	21
Synedra filiformis (M2)	0	0	20	0	0	5	0	0
Asterionella formosa (M2)	0	17	2	3	22	34	13	0
Cyclotella stelligera (M1)	34	11	1	0	0	0	0	0
Cyclotella sp.	3	12	9	0	0	0	0	0
Cyclotella comensis (M2)		13	12	0	0	11	23	0
Melosira granulata (E)	0	0	0	28	13	53	0	0

Table 25. The annual occurrence of dominant diatom forms with respect to each trophic level for 1975, 1976, 1977, 1978, 1979, 1980, 1981, and 1982 (5 months). (See Table 23 for definition of symbols M1, M2, and E).

	1975	1976	1977	1978	1979	1980	1981	1982
Mesotrophic, intolerant of nutrient enrichment	34	11	1	0	0	0	0	0
Mesotrophic, tolerant of moderate nutrient enrichment	47	70	92	57	62	125	74	79
Eutrophic	8	13	0	28	30	56	58	11

number of occurrences of eutrophic species was in 1981. A combination of decreasing occurrences of mesotrophic species that are intolerant of nutrient enrichment and of higher occurrences of eutrophic and mesotrophic species tolerant of moderate nutrient enrichment illustrates the continuing eutrophication of this region of Lake Michigan.

Important trends have been observed between 1975 and 1980 in entrainment assemblages (Table 26): 1) a doubling in the occurrence of the blue-green algae *Anacystis incerta*, *Gomphosphaeria lacustris*, and flagellates; 2) a large increase in the number of occurrences of chrysophycean flagellates; and 3) the continued increase in occurrence of dominant blue-green algae. The mechanisms which cause these changes are presently unknown; and, from the information available, it is difficult to offer a good explanation. Nevertheless, further study of these species may yield considerable insight into the factors influencing these changes. In 1981, there was a marked decrease in the blue-green spp. of *Anacystis incerta* and *Gomphosphaeria lacustris*, thus decreasing the dominant blue-green algae.

Table 26. The annual occurrence of dominant blue-green algae and flagellates in 1975, 1976, 1977, 1978, 1979, 1980, 1981, and 1982 (5 months).

	1975	1976	1977	1978	1979	1980	1981	1982
Flagellates	43	71	57	32	95	90	108	41
Chrysophycean flagellate (sp.)	1	4	24	23	27	19	73	64
Anacystis incerta	42	33	57	83	85	90	35	2
Gomphosphaeria lacustris	24	13	24	49	48	37	16	9
Dominant blue-green	66	46	81	132	133	127	51	11

Numbers of Forms, Diversity, and Redundancy --

When working with complex and variable assemblages of phytoplankton such as those appearing in entrainment samples from the nearshore of Lake Michigan, it is advantageous to use some quantitative measure of the distribution of populations within the various assemblages. Such measures can furnish information for assessing changes in community structure. The quantitative measures employed in this study are the number of species, diversity index, and redundancy.

The diversity index is calculated using the formula presented by Wilhm and Dorris (1968):

$$\bar{d} = -\sum_{i=1}^{S} (n_i/n) \log_2 (n_i/n)$$

where S is the number of species, n is the total number of phytoplankton in cells/mL, and n_i is the number of phytoplankton of the ith species. As not all forms encountered can be identified to the species level, the diversity index presented may differ somewhat from the true diversity measure.

Redundancy is a measure of the dominance of one or a few species within a population assemblage. As presented by Wilhm and Dorris (1968), it is:

$$r = \frac{\bar{d}_{max} - \bar{d}}{\bar{d}_{max} - \bar{d}_{min}}$$

where $\bar{d}$ is the diversity of a community as calculated above, $\bar{d}_{max}$ is the maximum diversity for the community, and $\bar{d}_{min}$ is the minimum diversity for the community. $\bar{d}_{max}$ and $\bar{d}_{min}$ are computed as follows:

$$\bar{d}_{max} = (1/n)(\log_2 n! - S\log_2 [n/S]!)$$

$$\bar{d}_{min} = (1/n)(\log_2 n! - S\log_2 [n-(S-1)]!)$$

The possible values of r vary between 0 and 1. When an r equals 0, it indicates that all the species encountered in a community have the same abundance; whereas, when an r equals 1, it implies that one species dominates a community. As shown in the formula, this value is derived from the measure of species number, abundance, and diversity.

The number of forms in the 1980 and 1981 entrainment samples showed a bimodal variation. The primary peak in 1980 was in September, with a lesser peak in June (Table 27 and Fig. 13). The number of forms varies from 41 to 70, with the minimum and maximum corresponding with the months of July and September, respectively. In 1981 the phytoplankton peaked in March, May, and September, with 66 forms in March and May and 65 forms in September. The minimum number of forms was 40 in July.

Species number fluctuations have long been an important issue. Many theories attempt to explain this phenomenon. The one offering the simplest and most plausible explanation for this was proposed by Moss (1973), who explained that different species begin to divide at different times of the year depending on their specific requirements for light, temperature, and nutrient types and levels. Most of these species are probably present in at least very small numbers throughout the year, and from these inocula larger populations can develop. After growth of a large population, decline occurs as the number of cells returns to the inoculum level. Population size depends on the balance between growth and concomitant loss by sinking, parasitism, and grazing. After the peak population has been reached, there is a rapid initial decline. As some

Table 27. Comparison of the number of forms of phytoplankton for the years 1975 through May 1982. Standard errors are included in the first set of parentheses and sample size is shown in the second set of parentheses.

Month	1975	1976	1977	1978	1979	1980	1981	1982
January	--- [1]	59.4(2.79)(11)	--- [1]	62.9(2.47)(11)	59.7(3.03)(18)	46.8(2.07)(17)	48.8(1.68)(18)	50.6(2.83)(18)
February	51.1(1.90)(9)	57.3(1.64)(12)	--- [1]	48.9(1.01)(12)	46.6(1.37)(18)	43.8(1.26)(18)	45.1(1.84)(18)	52.0(1.46)(12)
March	51.7(1.89)(9)	59.3(1.59)(12)	52.9(2.36)(12)	40.3(1.16)(12)	56.7(1.80)(18)	44.2(1.15)(18)	66.4(2.06)(12)	49.3(1.72)(18)
April	48.3(1.38)(9)	56.1(1.43)(12)	55.5(3.37)(12)	55.1(3.24)(12)	44.8(1.97)(12)	48.3(1.43)(18)	61.8(1.46)(12)	40.2(1.75)(18)
May	47.4(1.78)(9)	60.3(2.84)(12)	46.4(2.91)(12)	81.9(2.07)(12)	38.8(1.39)(12)	44.1(1.29)(18)	66.1(3.34)(12)	39.2(.992)(18)
June	49.2(1.77)(12)	65.8(1.77)(12)	64.1(3.59)(12)	85.3(4.17)(12)		53.2(2.02)(12)	42.8(2.47)(12)	--- [1]
July	51.6(.892)(12)	87.3(3.78)(12)	57.7(2.64)(12)	69.7(2.73)(18)	32.0(1.35)(12)	40.6(2.03)(12)	39.6(1.93)(12)	--- [1]
August	44.5(2.32)(12)	53.4(3.31)(12)	46.9(2.26)(12)	49.9(1.93)(18)	48.8(1.88)(18)	55.5(5.43)(18)	48.1(2.17)(18)	--- [1]
September	44.1(3.12)(10)	84.8(4.30)(12)	60.3(2.75)(12)	67.1(2.53)(18)	64.6(3.75)(16)	69.9(2.39)(18)	65.2(1.96)(18)	--- [1]
October	54.9(2.18)(12)	58.8(2.77)(12)	52.3(2.60)(12)	78.2(3.02)(18)	67.4(1.92)(18)	58.2(2.40)(18)	52.7(2.26)(12)	--- [1]
November	50.3(2.11)(12)	57.2(1.74)(12)	46.6(1.85)(12)	72.6(3.47)(12)	56.5(1.95)(12)	52.8(2.22)(12)	62.8(4.09)(12)	--- [1]
December	50.8(1.74)(11)	56.5(1.81)(12)	56.4(2.52)(12)	55.1(2.19)(13)	61.0(2.87)(12)	51.4(1.94)(12)	44.0(1.49)(18)	--- [1]
Yearly Mean	49.4(.969)	63.1(3.25)	53.9(1.92)	63.9(2.50)	52.4(3.36)	50.7(2.33)	53.6(2.94)	46.3(2.72)

[1] Samples were not collected where dashes appear.

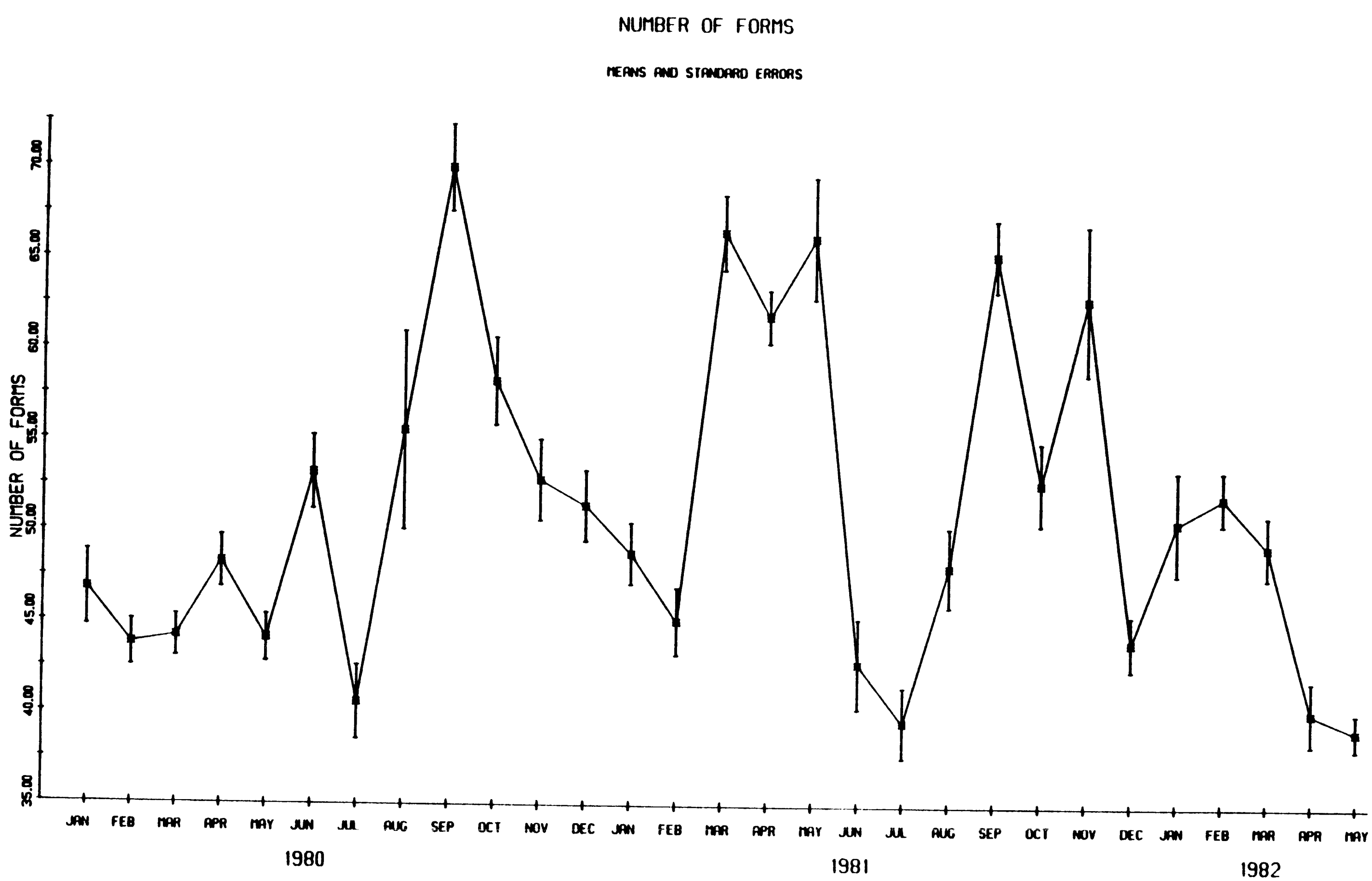

FIG. 13. Variation of number of forms during 1980, 1981, and 1982.

populations decline, others grow; and, with time, the complexity of overlap increases, leading to progressively greater diversity. This hypothesis seems to explain why the number of forms increased rapidly in late spring, late summer, or early autumn after an initial decline in spring and summer population. This hypothesis alone cannot fully illustrate all the changes in the system because the species fluctuation is also governed by many biotic and abiotic factors which vary from year to year. However, the increase in species numbers in summer has often been associated with upwelling which makes available hypolimnetic nutrients, including orthophosphate and silica, which stimulate the growth of some forms (Rossmann *et al.* 1979).

The diversity index is an estimate of the structure of communities. It measures the degree to which individuals are represented in an assemblage and is determined by the number of species and the degree of apportionment of individuals among species. For example, a diversity index varies with (1) large numbers of species, or (2) a high degree of apportionment of individuals among species, or (3) both of the above. In 1980, diversity reached its maximum in June and its minimum in August, corresponding with the values 4.16 and 3.58, respectively (Table 28 and Fig. 14). In 1981, the maximum was in May and the minimum in June, with values of 4.83 and 1.93, respectively. For both years, the minimum values do not coincide with the time when the minimum number of species occurred. The number of species does not always have a strong influence on the diversity index. This is because the diversity index depends on not only the number of species but also the codominancy of many species. Therefore, it is not uncommon that a sample with a high abundance in which one species is dominant has a relatively low diversity value. In fact, the cases of September 1977, October 1978, and September 1979 illustrate this situation: a large

Table 28. Comparison of phytoplankton form diversities for the years 1975 through May 1982. Standard errors are included in the first set of parentheses and sample size is shown in the second set of parentheses.

Month	1975	1976	1977	1978	1979	1980	1981	1982
January	--- [1]	4.29(.055)(11)	--- [1]	4.53(.092)(11)	4.34(0.102)(18)	3.79(0.087)(17)	4.17(.053)(18)	3.88(.057)(18)
February	4.35(.047) (9)	4.47(.059)(12)	--- [1]	4.37(.103)(12)	4.00(0.110)(18)	3.90(0.048)(18)	3.61(.071)(18)	3.79(.051)(12)
March	4.30(.054) (9)	4.34(.063)(12)	3.85(.068)(12)	3.69(.108)(12)	4.30(0.066)(18)	4.13(0.048)(18)	4.12(.070)(12)	3.93(.058)(18)
April	4.21(0.57) (9)	4.30(.047)(12)	4.36(.087)(12)	4.21(.119)(12)	3.82(0.078)(12)	3.72(0.060)(18)	4.42(.039)(12)	3.74(.061)(18)
May	3.76(.228) (9)	4.37(.112)(12)	2.98(.186)(12)	4.96(0.03)(12)	3.48(0.074)(12)	3.94(0.035)(18)	4.83(.073)(12)	3.19(.087)(18)
June	4.17(.081) (12)	4.67(.062)(12)	4.62(.084)(12)	4.31(0.10)(12)		4.16(0.055)(12)	1.93(.103)(12)	--- [1]
July	3.93(.065) (12)	5.08(.038)(12)	4.00(.056)(12)	4.86(0.05)(18)	3.24(0.089)(12)	3.87(0.051)(12)	3.35(.092)(12)	--- [1]
August	3.58(.163) (12)	3.50(.114)(12)	3.29(.161)(12)	4.07(0.97)(18)	3.82(0.061)(18)	3.58(0.125)(18)	2.82(.085)(18)	--- [1]
September	3.36(.189) (10)	4.92(.097)(12)	3.29(.109)(12)	4.40(0.15)(18)	3.55(0.084)(16)	4.00(0.060)(18)	3.58(.072)(18)	--- [1]
October	3.96(.138) (12)	4.48(.082)(12)	4.00(.076)(12)	3.77(0.11)(18)	4.15(0.083)(18)	3.79(0.102)(18)	3.66(.094)(12)	--- [1]
November	4.02(.119) (12)	3.97(.061)(12)	3.69(.094)(12)	3.58(0.11)(12)	3.81(0.046)(12)	3.76(0.076)(12)	4.22(.086)(12)	--- [1]
December	3.83(.0982)(11)	3.96(.096)(12)	3.82(.113)(12)	2.91(0.08)(18)	3.89(0.069)(12)	3.71(0.155)(12)	3.80(.030)(18)	--- [1]
Yearly Mean	3.95(.092)	4.36(.124)	3.79(.159)	4.15(0.09)	3.86(0.103)	3.86(0.05)	3.71(.222)	3.71(.133)

[1] Samples were not collected where dashes appear.

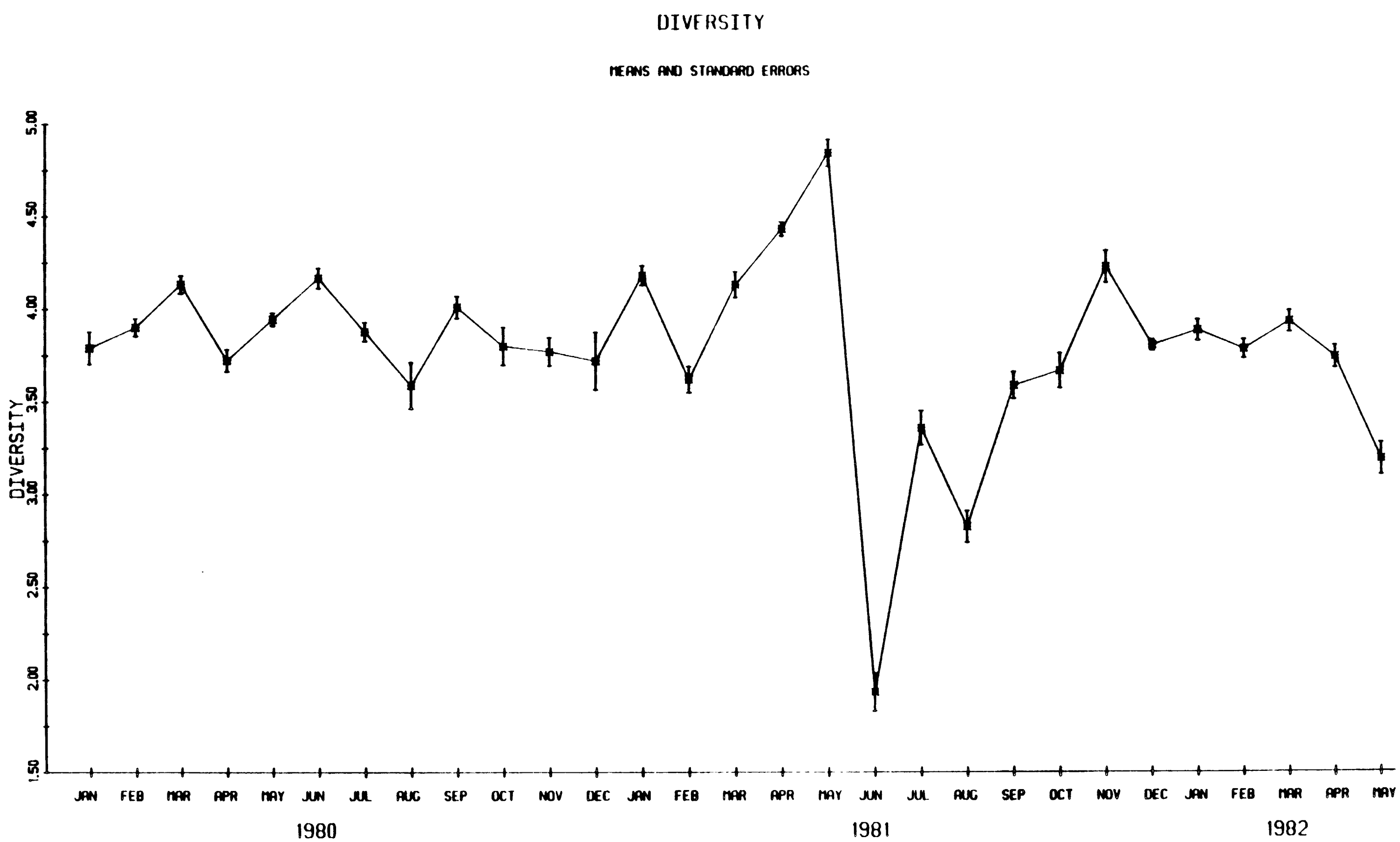

FIG. 14. Variation of diversity during 1980, 1981, and 1982.

number of species was encountered, but only one species, Anacystis incerta, was the dominant phytoplankter appearing at the time. Despite these exceptions, species number has often been significantly correlated with the diversity indices (Rossmann et al. 1980). In the open lake, the diversity index normally ranges from values slightly greater than zero (in bloom situations) to values as high as 4.5 (Tarapchak and Stoermer 1976). In this system, however, the monthly mean index of the 1980 entrained samples varied from 3.58 to 4.16, with an annual mean of 3.86; in 1981, the monthly mean varied from 1.93 to 4.83, with an annual mean of 3.71. According to the Margalef (1968) classification, the ranges of values corresponding to trophic states are as follows: oligotrophic, >3.5; mesotrophic, 2.5 to 3.5; and eutrophic, <2.5. Considering the annual mean of diversity, this geographic region is still far from a state in which any disturbance drastically changes algal community structure and thereby significantly reduces the diversity index.

In 1980, redundancy was low in March and high in August. In 1981, redundancy was low in May and high in June (Table 29, Fig. 15).

When the species numbers and the diversity and redundancy indices are compared annually, the number of species is high in 1976 and 1978, but low in 1975, 1977, 1979, 1980, and 1981; the diversity index is also at its peak in 1976 and 1978; 1980 and 1981 are similar to 1975, 1977, and 1979. The redundancy index, however, has its maximum in 1981 and its minimum in 1976.

Numbers and Biomass of Phytoplankton Passing Through the Plant --

One of the major stress factors unique to entrained phytoplankton is the artificially-elevated temperature in the condenser through which entrained phytoplankton must pass. The intake water temperature during 1979 varied from

Table 29. Comparison of phytoplankton redundancies for the years 1975 through May 1982. Standard errors are included in the first set of parentheses and sample size is shown in the second set of parentheses.

Month	1975	1976	1977	1978	1979	1980	1981	1982
January	--- [1]	.270(.011)(11)	--- [1]	.238(.016)(11)	.262(0.015)(18)	0.318(0.012)(17)	.254(.009)(18)	.315(.010)(18)
February	.230(.009)(9)	.231(.011)(12)	--- [1]	.207(.024)(12)	.278(0.020)(18)	0.286(0.012)(18)	.348(.014)(18)	.342(.007)(12)
March	.243(.008)(9)	.263(.011)(12)	.329(.008)(12)	.317(.021)(12)	.261(0.010)(18)	0.240(0.010)(18)	.323(.012)(12)	.301(.011)(18)
April	.246(.009)(9)	.260(.007)(12)	.244(.006)(12)	.272(.013)(12)	.303(0.012)(12)	0.337(0.013)(18)	.256(.007)(12)	.295(.009)(18)
May	.327(.054)(9)	.259(.015)(12)	.474(.030)(12)	.217(.007)(12)	.340(0.015)(12)	0.270(0.006)(18)	.197(.006)(12)	.402(.019)(18)
June	.258(.010)(12)	.223(.010)(12)	.223(.010)(12)	.329(.013)(12)		0.274(0.005)(12)	.661(.018)(12)	--- [1]
July	.310(.011)(12)	.210(.008)(12)	.318(.011)(12)	.201(.006)(18)	.358(0.014)(12)	0.270(0.010)(12)	.372(.017)(12)	--- [1]
August	.353(.026)(12)	.393(.017)(12)	.411(.034)(12)	.280(.009)(18)	.318(0.014)(18)	0.396(0.013)(18)	.504(.013)(18)	--- [1]
September	.389(.029)(10)	.227(.013)(12)	.457(.021)(12)	.447(.026)(18)	.422(0.012)(16)	0.394(0.008)(18)	.409(.012)(18)	--- [1]
October	.317(.021)(12)	.232(.014)(12)	.299(.011)(12)	.405(.017)(18)	.317(0.016)(18)	0.354(0.017)(18)	.363(.015)(12)	--- [1]
November	.289(.020)(12)	.322(.011)(12)	.335(.015)(12)	.427(.019)(12)	.348(0.011)(12)	0.334(0.016)(12)	.291(.009)(12)	--- [1]
December	.325(.017)(11)	.322(.018)(12)	.348(.019)(12)	.502(.017)(18)	.345(0.011)(12)	0.349(0.030)(12)	.303(.006)(18)	--- [1]
Yearly Mean	.299(.0152)	.268(.0154)	.344(.0262)	.320(0.030)	0.323(0.014)	0.316(0.014)	.357(.036)	.331(.020)

[1] Samples were not collected where dashes appear.

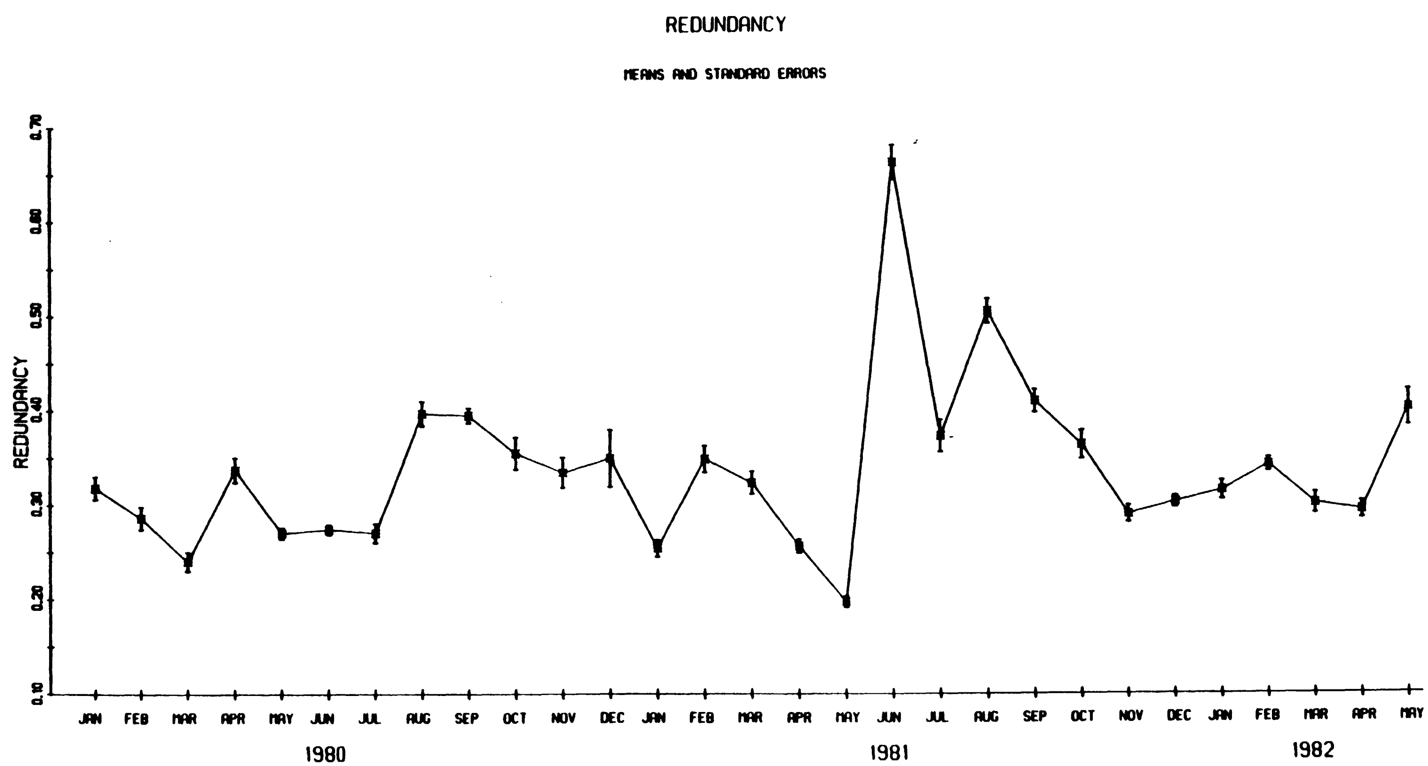

FIG. 15. Variation of redundancy during 1980, 1981, and 1982.

0.5°C to over 24.5°C; after the water had passed through the cooling system, its temperature at the discharge was about 10 C° higher. In the summer, the discharge water temperature approached 34°C, the temperature suggested by Patrick (1969) as having a harmful effect on algae. Because of possible harmful effects on algae, the numbers and biomass of phytoplankton passing through the condenser and the possible effect of this impact on phytoplankton were assessed.

The plant pumped water at an average rate of 2,700 m^3 min^{-1} for unit #1 and 3,500 m^3 min^{-1} for unit #2. When both units were in operation, the average rate at which water was pumped through the plant was 6,200 m^3 min^{-1}. The mean monthly total phytoplankton densities were used to estimate the number of phytoplankton passing through the plant in each month. The weight of the phytoplankton was then computed using the conversion coefficient of 0.57×10^{-9} gm as the average weight of a phytoplankton cell (Ayers and Seibel 1973). Using these methods, an estimate of the number of phytoplankton cells and their weight has been calculated for every month studied (Table 30). Not all the annual estimates began in January, and the units in operation were different in each year; therefore, it is not appropriate to make annual comparisons of the total entrained phytoplankton in numbers or weight. Furthermore, the above estimates were based on the assumption that the plant was operating 100% of the time and that no recirculation of discharge water occurred. Thus, the monthly estimate represents a somewhat inflated value for the number and weight of phytoplankton passing through the plant during each month.

Table 30. Phytoplankton entrained by the plant during 1976, 1977, 1978, 1979, 1980, 1981, and the first five months of 1982. --- indicates no data.

	Numbers Entrained						
Month	1976	1977	1978	1979	1980	1981	1982
January	4.25×10^{17}	---------	1.79×10^{17}	3.03×10^{17}	5.41×10^{17}	3.91×10^{17}	3.34×10^{17}
February	1.59×10^{17}	---------	5.06×10^{16}	1.85×10^{17}	2.16×10^{17}	2.78×10^{17}	4.02×10^{17}
March	2.22×10^{17}	2.87×10^{17}	8.21×10^{16}	3.68×10^{17}	3.06×10^{17}	7.04×10^{17}	7.19×10^{17}
April	3.49×10^{17}	4.32×10^{17}	2.27×10^{17}	5.82×10^{17}	4.53×10^{17}	1.04×10^{18}	1.20×10^{18}
May	5.45×10^{17}	2.13×10^{17}	7.58×10^{17}	6.21×10^{17}	1.65×10^{18}	3.05×10^{18}	6.54×10^{17}
June	1.81×10^{17}	1.83×10^{17}	1.09×10^{18}	---------	1.35×10^{18}	7.47×10^{17}	
July	9.57×10^{17}	2.53×10^{17}	1.08×10^{18}	1.85×10^{17}	6.19×10^{17}	5.16×10^{17}	
August	3.79×10^{17}	2.48×10^{17}	4.05×10^{17}	3.48×10^{17}	9.49×10^{17}	8.85×10^{17}	
September	5.89×10^{17}	1.88×10^{17}	3.63×10^{17}	4.63×10^{17}	1.25×10^{18}	1.94×10^{18}	
October	3.28×10^{17}	3.07×10^{17}	1.26×10^{18}	7.70×10^{17}	1.28×10^{18}	8.58×10^{17}	
November	3.60×10^{17}	3.56×10^{17}	9.91×10^{17}	6.82×10^{17}	1.16×10^{18}	1.26×10^{18}	
December	3.46×10^{17}	2.11×10^{17}	1.36×10^{18}	1.15×10^{18}	8.09×10^{17}	9.70×10^{17}	
Total	4.84×10^{18}	2.68×10^{18}	7.85×10^{18}	5.66×10^{18}	1.06×10^{19}	1.26×10^{19}	3.31×10^{18}

(Continued)

Table 30. (Concluded).

Month	Weight Entrained (gms)						
	1976	1977	1978	1979	1980	1981	1982
January	$2.42x18^{8}$	----------	$1.02x10^{8}$	$1.73x10^{8}$	$3.08x10^{8}$	$2.23x10^{8}$	$1.90x10^{8}$
February	$9.06x10^{8}$	----------	$2.89x10^{7}$	$1.05x10^{8}$	$1.23x10^{8}$	$1.58x10^{8}$	$2.29x10^{8}$
March	$1.27x10^{8}$	$1.64x10^{8}$	$4.68x10^{7}$	$2.10x10^{8}$	$1.74x10^{8}$	$4.01x10^{8}$	$4.10x10^{8}$
April	$1.99x10^{8}$	$2.46x10^{8}$	$1.30x10^{8}$	$3.09x10^{8}$	$2.58x10^{8}$	$5.91x10^{8}$	$6.87x10^{8}$
May	$3.11x10^{8}$	$1.21x10^{8}$	$4.34x10^{8}$	$3.54x10^{8}$	$9.43x10^{8}$	$1.74x10^{9}$	$3.73x10^{8}$
June	$1.04x10^{8}$	$1.03x10^{8}$	$6.24x10^{8}$	--------	$7.68x10^{8}$	$4.26x10^{8}$	
July	$5.45x10^{8}$	$1.44x10^{8}$	$6.14x10^{8}$	$1.06x10^{8}$	$3.53x10^{8}$	$2.94x10^{8}$	
August	$2.16x10^{8}$	$1.41x10^{8}$	$2.30x10^{8}$	$1.98x10^{8}$	$5.41x10^{8}$	$5.04x10^{8}$	
September	$3.36x10^{8}$	$1.07x10^{8}$	$2.07x10^{8}$	$2.64x10^{8}$	$7.15x10^{8}$	$1.11x10^{9}$	
October	$1.87x10^{8}$	$1.75x10^{8}$	$7.15x10^{8}$	$4.39x10^{8}$	$7.29x10^{8}$	$4.89x10^{8}$	
November	$2.05x10^{8}$	$2.03x10^{8}$	$5.66x10^{8}$	$3.89x10^{8}$	$6.62x10^{8}$	$7.18x10^{8}$	
December	$1.97x10^{8}$	$1.20x10^{8}$	$7.73x10^{8}$	$6.56x10^{8}$	$4.61x10^{8}$	$5.53x10^{8}$	
Total	$2.76x10^{9}$	$1.53x10^{9}$	$4.47x10^{9}$	$3.20x10^{9}$	$6.04x10^{9}$	$7.20x10^{9}$	$1.89x10^{9}$

CHLOROPHYLLS AND PHAEOPHYTIN *a*

The complete results of the chlorophyll *a*, *b*, *c*, and phaeophytin *a* analysis from January 1980 through May 1982 are contained in Appendix 2. These data have been used 1) to assess the immediate and delayed impact of entrainment on phytoplankton viability and 2) to monitor the monthly fluctuations in these pigments with respect to the observed phytoplankton densities.

Assessment of Damage to Phytoplankton

Because disruption of the photosynthetic mechanism could result in the inhibition or death of the algae, analysis of the photosynthetic pigment concentration is used to assess viability changes associated with condenser passage. The chlorophyll molecule degrades to three pigments (phaeophytin, phaeophorbide, and chlorophyllide). Phaeophytin (also measured in this analysis) is formed when

$$\begin{tikzcd}
\text{CHLOROPHYLL} \arrow[r, "-\text{phytol}"] \arrow[d, "-\text{Mg}"'] & \text{CHLOROPHYLLIDE} \arrow[d, "-\text{Mg}"'] \\
\text{PHAEOPHYTIN} \arrow[r, "-\text{phytol}"] & \text{PHAEOPHORBIDE}
\end{tikzcd}$$

chlorophyll loses its central Mg atom. Subsequent loss of the phytol side-chain results in pheophorbide. Chlorophyllide is formed by the enzymatic removal of the phytol group from the chlorophyll molecule. Additional loss of the Mg atom produces phaeophorbide. Each of these pigments may be broken down into small colorless compounds or oxidized.

Chlorophyll *a*, the primary photosynthetic pigment, is found in all groups of algae and occurs in much higher concentrations than either chlorophylls *b* or *c*; it is the best chlorophyll for the assessment of intake/discharge differences. Chlorophylls *b* and *c*, while significant for comparison with the major

groups of phytoplankton, do not exhibit any consequential patterns relating to entrainment. The phaeophytin a to chlorophyll a ratio is relatively insensitive to changes of the magnitude that occur during entrainment, but it is also of some interest to the discussion of monthly pigment variation and seasonal succession.

The occurrence of statistically significant ($\alpha < 0.05$) differences between pigment concentrations of intake and discharge water for all 1980, 1981, and 1982 samples are summarized in Tables 31 and 32. The differences are presented as percentages of the number of sample sets (N) for each year. There are three non-incubated and one incubated sample sets per month.

As is evident from Table 31, the chlorophyll a concentration decreases more frequently than it increases, indicating that at least some of the pigment is altered during condenser passage. However, it is either not becoming or not remaining phaeophytin a, because there is no apparent increase in the degradation product after entrainment. In fact, the data indicate that phaeophytin a actually decreases. It is possible 1) that the phaeophytin a is broken down further to phaeophorbide, 2) that the chlorophyll a and/or the phaeophytin a may be degraded to small or colorless compounds, or 3) that the chlorophyll is becoming chlorophyllide.

The cellular metabolism may be disrupted without any immediately detectable damage to the photosynthetic system. An assessment of delayed effects was attempted by the analysis of pigment concentration in samples 36 hours after collection. Data on the incubated samples will be dealt with in the discussion of chlorophyll a data for all study years.

Table 31. Percent of non-incubated sample sets which showed statistically significant ($\alpha < 0.05$) differences between pigment concentrations of intake and discharge water. The number of sample sets (N) and the phaeophytin a to chlorophyll a ratio are included.

	N	Chl. a (%)	Chl. b (%)	Chl. c (%)	Phaeo a (%)	Ratio (%)
Increased						
1980	36	3	0	6	3	3
1981	36	3	8	3	0	0
1982	15	13	0	7	0	0
Decreased						
1980	36	17	3	0	0	0
1981	36	14	0	3	6	6
1982	15	13	7	7	20	13

Table 32. Percent of incubated sample sets which showed statistically significant ($\alpha < 0.05$) differences between pigment concentrations of intake and discharge water. The number of sample sets (N) and the phaeophytin a to chlorophyll a ratio are included.

	N	Chl. a (%)	Chl. b (%)	Chl. c (%)	Phaeo a (%)	Ratio (%)
Increased						
1980	12	8	0	0	0	0
1981	12	17	0	0	0	0
1982	5	0	0	20	0	0
Decreased						
1980	12	8	0	0	8	8
1981	12	25	8	25	25	25
1982	5	0	0	0	0	0

Table 33 contains a comparison of the combined chlorophyll data for all study years. The values presented are the number of significant changes in all variables divided by the total number of comparisons for each year, and they are shown as percentages. There were 240 comparisons in 1980 and 1981, and 100 in 1982 (see Appendix 2). The difference between 1975-76 and subsequent years has been attributed to a methodology change (Rossmann et al. 1977). No consistent trends in viability are evident and only 1977 shows a notable difference between the occurrence of increases and decreases in pigment concentrations. The mean and standard deviation ($\bar{x}, \sigma$) for all years are also indicated in the table.

The chlorophyll a data from Tables 31 and 32 are combined with data from previous years in Table 34. The difference between the instances of increases and decreases in the non-incubated samples of 1980-82 is consistent with earlier data. Although the years 1975, 1979, and 1982 are notable exceptions, overall, the data indicate that some decrease in viability does occur during condenser passage. Comparison of the incubated and non-incubated samples provides some information on the delayed effects of entrainment on phytoplankton viability. Delayed damage would be indicated if the percentage of incubated samples showing decreased chlorophyll a concentration were high compared with the non-incubated samples. Only 1977 and 1981 exhibit this pattern, with the remaining data indicating that no additional viability decrease occurs within 36 hours after entrainment. Between 1978 and 1981, the somewhat higher percentage of incubated samples showing an increase (compared with non-incubated) indicates that cell division occurred during incubation and implies that the algae may have been mildly stimulated by entrainment.

Table 33. Percent occurrence of statistically significant changes in all comparisons between intake and discharge.

Year	Percent of Comparisons Showing Increase	Percent of Comparisons Showing Decrease
1975	2	4
1976	4	5
1977	1	16
1978	9	9
1979	9	5
1980	3	2
1981	8	5
1982 (through May)	11	7
	$\overline{X}$ = 5.9	6.6
	σ = 3.8	4.3

Table 34. Percent occurrence of statistically significant changes in chlorophyll a concentration between intake and discharge.

Year	Increase		Decrease	
	Non-Incubated	Incubated	Non-incubated	Incubated
1975	0	0	0	5
1976	6	0	8	8
1977	0	0	30	60
1978	5	17	22	17
1979	16	30	15	12
1980	3	8	17	8
1981	3	17	14	25
1982 (through May)	13	0	13	0
	$\overline{X}$ = 5.8	9.0	14.9	16.9
	σ = 5.9	11.3	8.9	19.0

Although condenser passage appears to alter phytoplankton metabolism to some degree, more quantitative conclusions are hampered by our inability to sample from exactly the same "parcel" of water before and after condenser passage. High variability between samples is evident in the chlorophyll data, as well as the species counts, and may be due in part to the "patchiness" of the phytoplankton in the lake. Furthermore, chlorophyll analysis, while providing an indication of the phytoplankton's gross condition (dead or alive), is not sensitive enough to subtle changes in viability of the degree likely to occur during entrainment. Primary productivity data based on uptake of C-14 indicate that a reduction in the photosynthetic rate occurs even though little significant change in chlorophyll *a* is observed (Chang *et al*. 1981b). Factors causing the rate reduction and details concerning the duration of the change are still unclear.

Monthly Variation of the Chlorophylls and Phaeophytin *a*

Data from the intake samples are used to monitor monthly chlorophyll and phaeophytin *a* fluctuations. The results for January 1980 through May 1982 are illustrated in the figures which follow. Comparison of these with the major group plots (Figs. 3-12) gives an indication of the origins of chlorophyll peaks. Chlorophyll *a* (Fig. 16) is present in all major groups of algae and the monthly levels are associated closely with the seasonal succession of phytoplankton (Total Algae, Fig. 12). All years show regular spring and fall peaks. Spring chlorophyll *a* peaks resulted primarily from the high abundance of diatoms, while the fall increases were caused by greens, coccoid blue-greens, and diatoms.

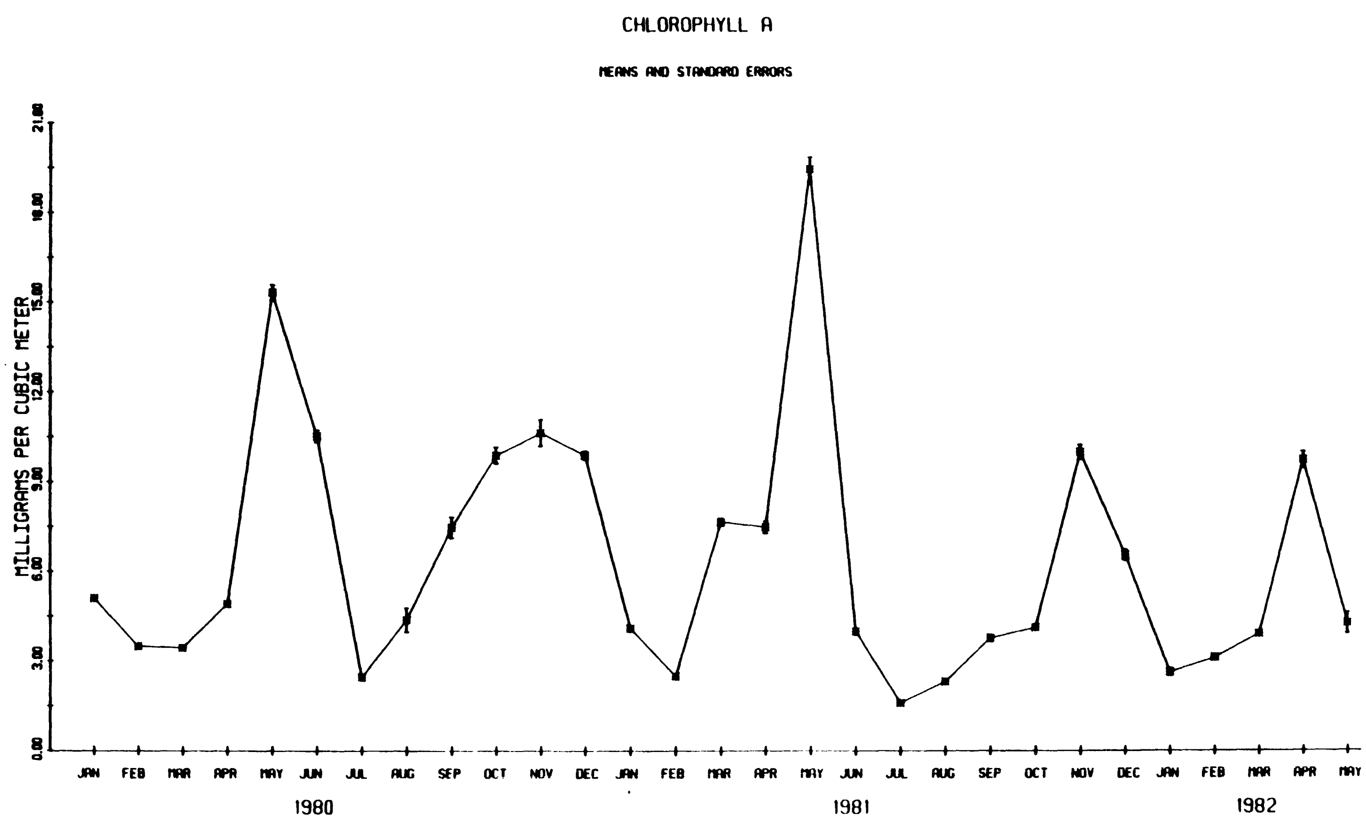

FIG. 16. Variation of chlorophyll a concentrations during 1980, 1981, and 1982.

Chlorophyll b (Fig. 17) is found primarily in green algae. In addition to the coccoid and filamentous groups, flagellates and especially Other Algae may contain sizable green algae components. The green species of flagellates made a major contribution to the April 1980 chlorophyll b peak; and the greens in Other Algae, along with the coccoid greens, were the important constituents of the Fall 1980 increase. A single species of filamentous green algae appears responsible for the chlorophyll b peak in May 1981. The original phytoplankton counts for that month (see Appendix 1) indicate a high abundance of *Ulothrix* sp. in one of the samples. The large peak in January 1982 must be attributed to experimental error, because no group of algae occurred in numbers sufficient to produce such an increase.

Pennate and centric diatoms are the principal contributors of chlorophyll c in the phytoplankton samples, and the chlorophyll c plot (Fig. 18) follows the seasonal succession of diatoms. Chrysophycean flagellates, dinoflagellates, and cryptomonads (lumped into the major group Flagellates) also contain the pigment; but their combined biomass is considerably less than that of the diatom fraction.

The phaeophytin a levels (Fig. 19) generally follow the pattern seen in chlorophyll a, although the actual concentration of phaeophytin remains well below that of chlorophyll. The peak in May 1981 is larger than usual but is in line with the high abundance of phytoplankton observed for that month. The ratio of phaeophytin a to chlorophyll a (Fig. 20) was high in April 1980, prior to the spring phytoplankton bloom. This increase may have resulted from the spring turnover, when decaying algae are brought up from the bottom. The ratio remained relatively low through the rest of 1980 and early 1981. In May 1981, the ratio increased sharply, possibly again as the result of turnover.

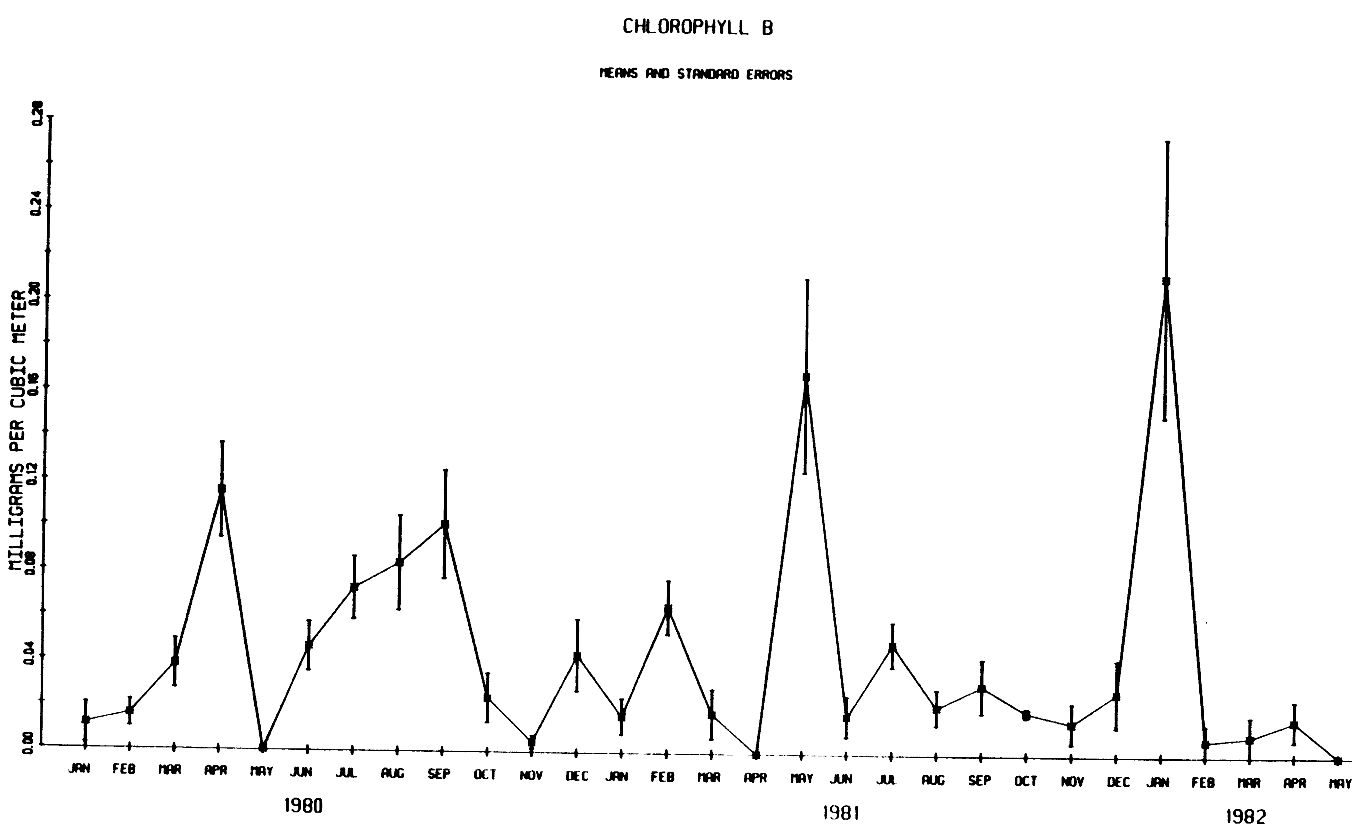

FIG. 17. Variation of chlorophyll b concentrations during 1980, 1981, and 1982.

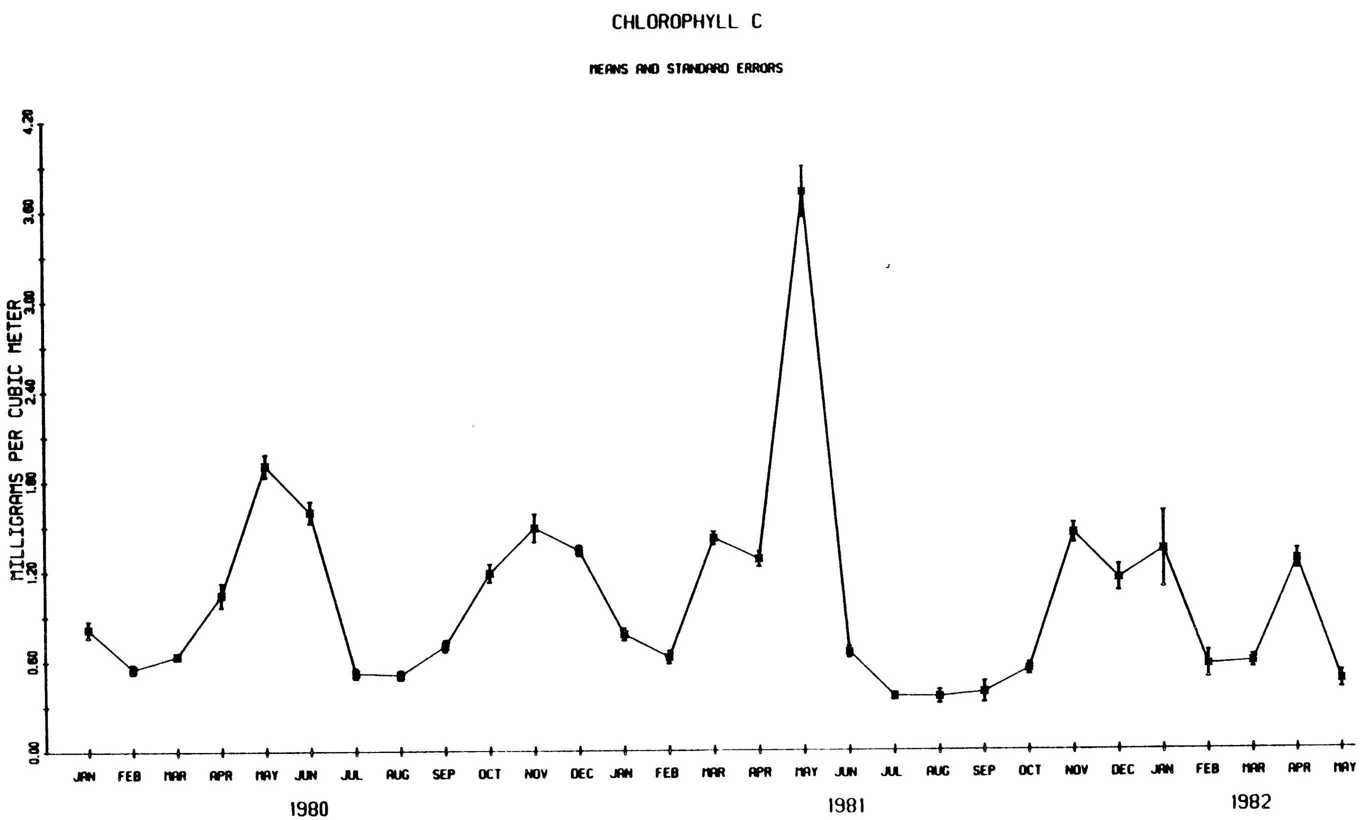

FIG. 18. Variation of chlorophyll c concentrations during 1980, 1981, and 1982.

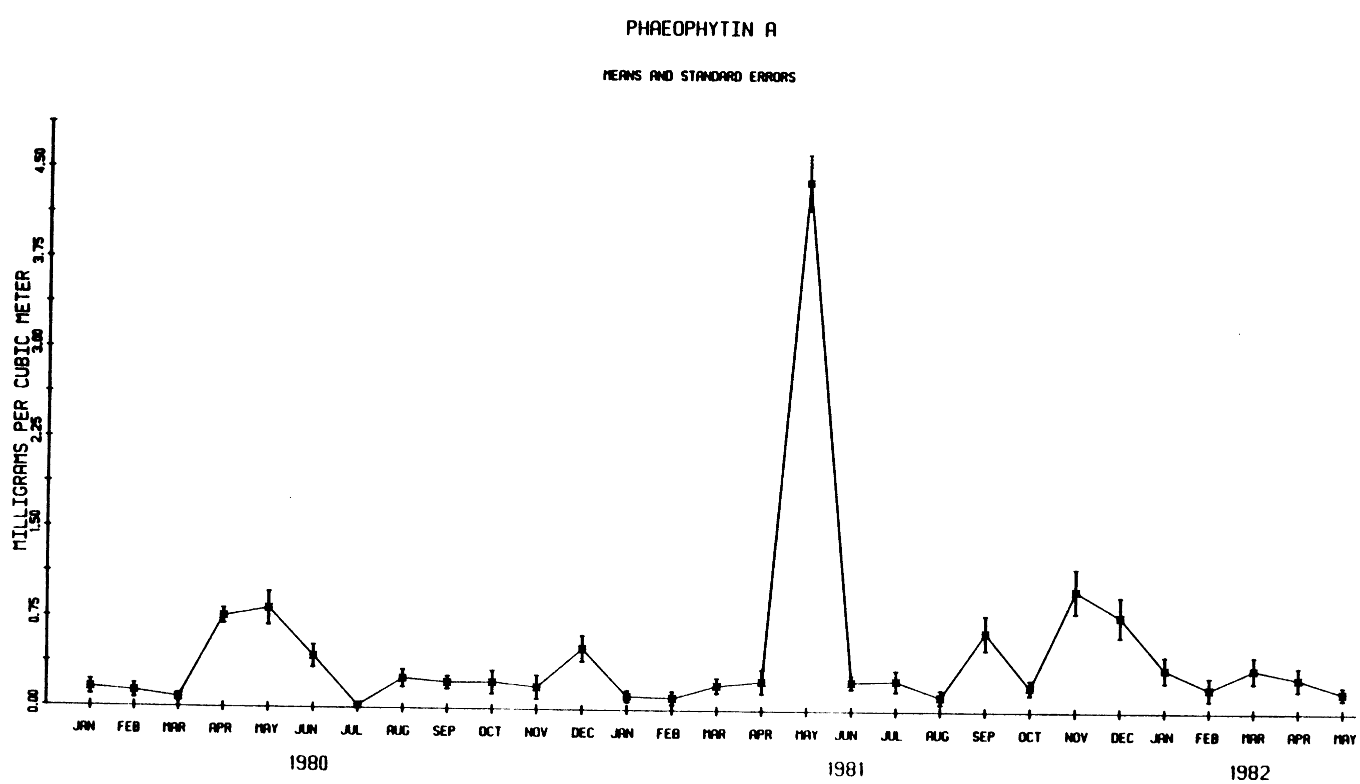

FIG. 19. Variation of phaeophytin a concentrations during 1980, 1981, and 1982.

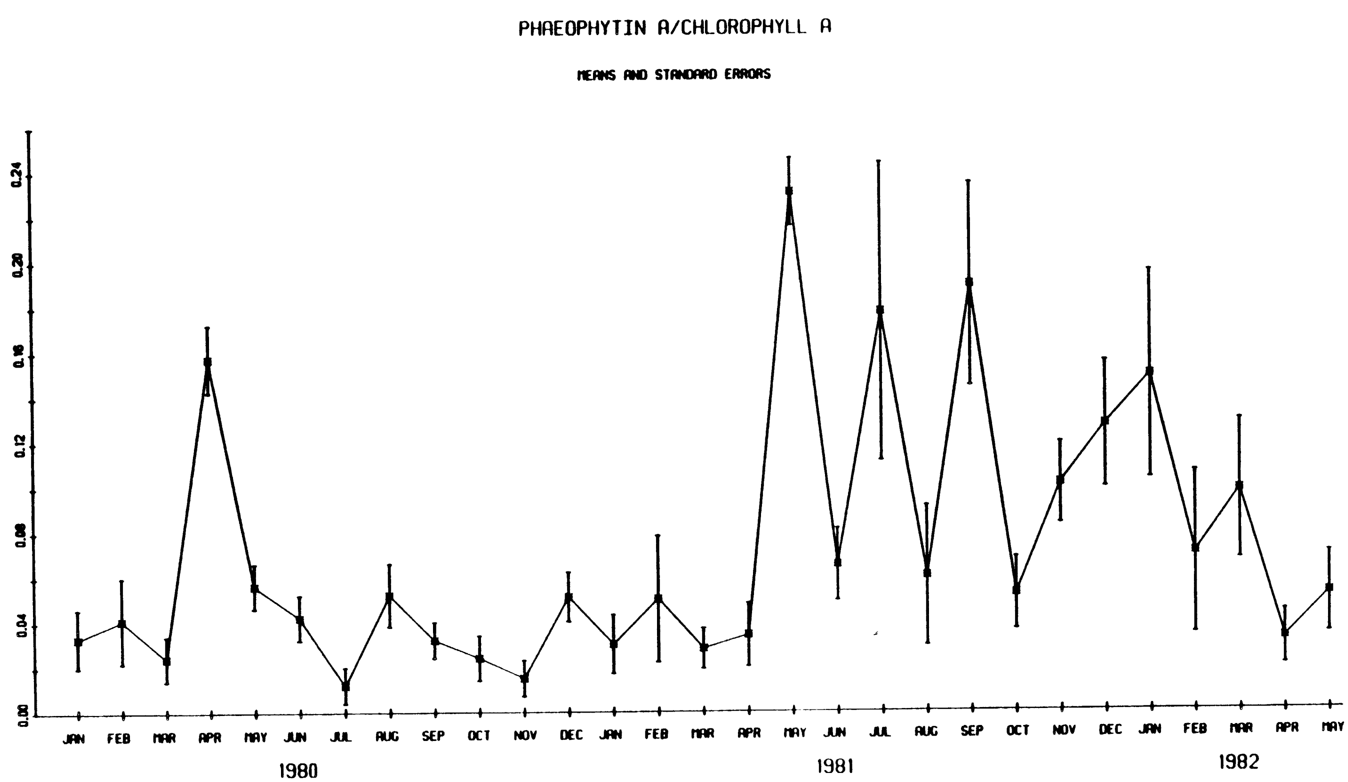

FIG. 20. Variation of the phaeophytin a/chlorophyll a ratio during 1980, 1981, and 1982.

The points from June through September are difficult to interpret, but the gradual rise in the ratio from October 1981 through January 1982 was probably the result of the decline of the winter bloom.

SUMMARY

In 1980, orthophosphate concentration ranged from 0.11 ppb during maximum utilization in June to 1.25 ppb in October, after the onset of fall turnover. Nitrate varied from 0.143 ppm (September) to 0.5 ppm (April), and nitrite was detectable in January, April, and June. Dissolved silica concentrations ranged from 1.36 ppm during the spring turnover in April down to 0.06 ppm after the winter bloom.

For 1981, orthophosphate was at its minimum level of 0.215 ppb during the diatom bloom in November and at its maximum of 1.83 ppb, atypically, in December. Nitrate ranged from 0.11 ppm in June to 0.481 in December; and nitrite was present in April, July, August, October, November, and December. Dissolved silica varied from 0.409 ppm in August, well after the May diatom bloom, to 2.22 ppm in March, perhaps as a result of runoff combined with the beginning of turnover. It exceeded 1.0 ppm in January (1.18), February (1.53), March (2.22), October (1.42), November (1.02), and December (1.68).

In the 1982 samples available, orthophosphate generally decreased between the maximum in January (0.979 ppb) and the minimum in May (0.0409 ppb). Nitrite appeared in April, with spring turnover. Spring maximums for dissolved silica (1.2 ppm) and nitrate (0.453 ppm) also occurred in April. Utilization was evident in May, when the dissolved silica concentration was 0.314 ppm and the nitrate concentration was 0.0303 ppm.

Coccoid blue-green algae were low in concentration during February through May and high in concentration from July through December 1980. In 1981, concentrations were low from January through July and high in September, with a decrease from October through December. Concentrations were low in 1982 from

January through May. Filamentous blue-green algae were less numerous than coccoid blue-green algae and peaked in June 1980 and May 1981, with 312 cells/mL and 111 cells/mL, respectively. Coccoid green algae were relatively high during July through September 1980 and July 1981. Filamentous green algae reached 9 cells/mL in May 1980 and 85 cells/mL in May 1981, thus constituting a minor portion of the total algal population. Flagellates were numerous and contributed an important share to the total annual algal population. They peaked in April 1980 and were low during October through December 1980. In 1981, flagellates peaked in June and were considerably higher than 1980 for the remainder of the year. The yearly means for 1981 and 1982 were the highest for 1975-1982. Centric diatoms peaked in May and September 1980; May, September, and November 1981; and April 1982. Pennate diatoms were most abundant in May and November 1980; May and December 1981; and April and May 1982. Desmids were consistently low during 1980-1982, reaching 5 cells/mL in May 1981. Other algae had peak abundances in September 1980, and April and September 1981. Total algae numbers were highest in May, September, October, and November 1980; May, September, and November 1981; and April 1982.

Comparison of phytoplankton major group mean concentrations for 1975 to May 1982 gave the following general observations: 1) coccoid blue-green algae and desmids were least abundant during 1976; 2) coccoid green algae and centric diatoms were least abundant in 1977; 3) flagellates were least abundant in 1979-1980; 4) filamentous blue-greens were least abundant in 1981; 5) filamentous green algae were most abundant in 1976, and other algae were most abundant in 1981; 6) total algae and pennates were least abundant in 1979. The reason for this low count in 1979 may be the absence of June samples, when the

abundance is usually high. The value for the yearly average may, therefore, be unduly low.

The number of forms of phytoplankton identified during 1980 varied from 41 in July to 70 in September. In 1981, forms varied from 40 in July to 65 in September. Diversity ranged from 3.58 in August to 4.16 in June during 1980, and from 1.93 in June to 4.83 in May 1981; and redundancy varied from 0.240 in March to 0.396 in August 1980, and from 0.197 in May to 0.661 in June during 1981.

The average number of forms and the redundancy index were highest in 1978 and 1981, respectively; and diversity was highest in 1976 and lowest in 1981.

Important trends have been observed in entrainment assemblages: 1) a continuous frequent occurrence and large abundance of the blue-green alga *Anacystis incerta* through 1980, followed by a substantial decrease in 1981; 2) decline in the occurrence of *Gomphosphaeria lacustris* in 1980-1981; 3) a large increase in the occurrence of flagellates and chrysophycean flagellates through 1981; and 4) a continued increase in the occurrence of dominant blue-green algae through 1979, and then a sharp decline in 1981.

A combination of decreasing occurrences of mesotrophic species that are intolerant of nutrient enrichment and of higher occurrences of eutrophic and mesotrophic species tolerant of moderate nutrient enrichment illustrates the continuing degradation of this southern sector of Lake Michigan.

Viability results based on the comparisons of chlorophyll and phaeophytin concentrations of intake and discharge samples were variable and lacked consistent trends in the years (1975-1982) under consideration. Only 1977 showed a significant decrease in viability after condenser passage, with 16% of the sampling periods exhibiting lower chlorophyll levels and only 1% having higher

levels after entrainment. However, comparison of chlorophyll a concentrations before and after condenser passage shows a lower concentration for all study years except 1979, indicating that some damage does occur. Chlorophyll a levels in the incubated samples imply a delayed stimulatory effect on viability but are inconclusive because of the high variability of the samples.

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